FACULTY OF TECHNOLOGY

USE OF GROUND SOURCE HEAT TECHNOLOGIES FOR HEATING BUILDINGS: CASE STUDY OF KUIVANIEMEN KOULU

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ABSTRACT

Use of ground source heat technologies for heating buildings: case study of Kuivaniemen koulu

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This study was done to determine the current state and feasibility of medium-depth ground source heat pump systems in Finland, and its applicability at a study site in the municipality of Ii. A school, day-care centre and two terraced houses located at one property were chosen as the study site due to their need for a new heating system to replace district heating in the coming years. Medium-depth ground source heat pump system was also compared to a conventional ground source heat pump system, which have shallower boreholes, to define the advantages and disadvantages of both technologies. In addition, the feasibility of utilising load shifting as a demand-side management tool was studied in order to generate savings in electricity bill and to make a medium-depth ground source heat pump system more affordable at the study site.

Currently, there is only one operating medium-depth ground source heat pump in Finland and another should start operating during 2020. Compared to conventional ground source heat pumps they have higher investment costs because drilling becomes more expensive when depth increases. It is expected, however, that the costs will decrease if medium-depth boreholes become more common. The interest towards deeper boreholes is caused by the higher temperature deep in the ground which provides higher energy production. In addition, unlike medium-depth boreholes, shallow boreholes require a larger area which is not always available at urban areas. Medium-depth ground source heat pumps seem to be the most suitable for buildings which do not have enough space for shallow boreholes and which have both high heating and cooling demand.

The feasibility study of both heating systems and load shifting as a demand-side management tool at the study site included several uncertainties due to lack of information of the study site and experience of medium-depth ground source heat pump systems.

Without extensive research of the ground properties, it is hard to determine the production rate of especially medium-depth boreholes and therefore the heat production is only an estimate. Nevertheless, one medium-depth borehole was estimated to be able to cover the thermal energy demand of the school and day-care centre but not the terraced houses. Shallow boreholes could be constructed to cover the energy demand of all buildings, but they would require a vast area at the property since 29 boreholes would be required. The payback time of a medium-depth ground source heat pump system for the educational buildings was determined to be 13 years and the payback time of a shallow ground source heat pump system for all buildings would be 12 years.

The biggest drawback of shallow boreholes is the challenge to fit them to the property. If all 29 shallow boreholes were constructed, some trees might have to be cut down and some of the boreholes would have to be located at places where children play during their breaks. Because a medium-depth borehole could only cover the energy need of the school and day-care centre, eight shallow boreholes should be constructed in addition to the medium-depth borehole in order to also secure the heating of the terraced houses. Nevertheless, fitting of nine boreholes is significantly easier than fitting of 29 boreholes. Alternatively, the terraced houses could be heated for example with electric heating if district heating is no longer in use.

The proposal of using demand-side management was to preheat the school building at night when electricity is cheaper, which would enable turning off the heating in the morning when electricity price is the highest. Because ground source heat pump systems use electricity and real-time electricity prices are highest in the morning, the plan would decrease the average price which is payed for electricity. It was calculated in the study that depending on the length of preheating, annually around 100 MWh of heat generation from the morning could be shifted to nighttime resulting in moderate annual savings of approximately 400 €. Even though it was not considered in the study, load shifting would probably increase the amount of purchased electricity and decrease the calculated savings. Because the estimated savings are very small compared to annual heating costs and investment costs of a ground source heat pump system, the studied method to utilise demand-side management does not seem to be a very profitable investment.

Keywords: geothermal energy, medium-depth ground source heat, demand-side management

TIIVISTELMÄ

Use of ground source heat technologies for heating buildings: case study of Kuivaniemen koulu

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Tämän työn tarkoituksena oli selvittää keskisyvän maalämmön käyttökelpoisuus yleisesti Suomessa ja Iissä sijaitsevassa tutkimuskohteessa. Samalla tontilla sijaitsevat koulu, päiväkoti ja kaksi rivitaloa valittiin tutkimuskohteeksi, sillä ne tarvitsevat mahdollisesti uuden lämmitysjärjestelmän korvaamaan kaukolämmön tulevien vuosien aikana. Keskisyvää maalämpöä verrattiin myös tavalliseen maalämpöön eli matalampiin lämpökaivoihin, jotta lämmitysjärjestelmien edut ja haitat pystytään määrittämään. Lisäksi kysynnänhallinnan käyttämisen mahdollisuutta selvitettiin työssä sähkölaskujen pienentämiseksi ja keskisyvän maalämmön kannattavuuden parantamiseksi.

Tällä hetkellä Suomessa on vain yksi toiminnassa oleva keskisyvä maalämpökaivo ja toisen pitäisi aloittaa toiminta kuluvana vuonna 2020. Mataliin lämpökaivoihin verrattuna keskisyvillä maalämpökaivoilla on korkeammat investointikustannukset, sillä poraaminen kallistuu syvyyden kasvaessa. Odotetaan kuitenkin, että kustannukset laskevat keskisyvän maalämmön tullessa suositummaksi. Kiinnostus keskisyvään maalämpöön johtuu korkeammasta lämpötilasta syvemmällä maassa, joka aiheuttaa myös korkeamman energiantuotannon. Lisäksi toisin kuin keskisyvä maalämpökaivo, matalat maalämpökaivot vaativat suuren alueen, jota ei ole aina saatavilla kaupunkialueilla. Keskisyvä maalämpö vaikuttaa olevin sopivin rakennuksiin, joilla ei ole tarpeeksi tilaa mataliin maalämpökaivoihin ja joilla on sekä korkea lämmitys- että jäähdytystarve.

Molempien lämmitysjärjestelmien ja kysynnänhallinnan kannattavuuden tutkimisessa oli useita epävarmuuksia tutkimuskohteen tietojen ja keskisyvän maalämmön käyttökokemuksien puutteen vuoksi. Ilman tarkkaa tutkimuskohteen maaperän tutkimista on vaikea määrittää maalämpökaivon lämmöntuotantoa ja sen vuoksi lämmöntuotannon määrä on vain arvio. Työssä arvioitiin kuitenkin, että yksi keskisyvä maalämpökaivo

voisi tuottaa tarpeeksi energiaa koululle ja päiväkodille, mutta ei rivitaloille. Matalia lämpökaivoja voitaisiin käyttää tuottamaan lämpöä kaikille rakennuksille, mutta se vaatisi paljon tilaa tontilla, sillä kaivoja tarvittaisiin 29. Pelkän keskisyvän maalämpökaivon takaisinmaksuajaksi määritettiin 13 vuotta ja 12 vuotta maalämpöjärjestelmälle, joka käyttää matalia lämpökaivoja ja tuottaa lämpöä kaikille rakennuksille.

Matalien maalämpökaivojen isoin haittapuoli on niiden mahduttaminen tontille. Jos 29 matalaa lämpökaivoa porattaisiin, joitakin puita jouduttaisiin mahdollisesti kaatamaan ja lämpökaivoja jouduttaisiin sijoittamaan alueille, joissa lapset leikkivät. Koska keskisyvä maalämpökaivo voisi tuottaa vain koulun ja päiväkodin energiantarpeen verran energiaa, kahdeksan matalaa lämpökaivoa pitäisi porata keskisyvän lämpökaivon lisäksi, jotta myös rivitalojen lämmitys turvattaisiin. Yhdeksän porakaivon mahduttaminen olisi silti selvästi helpompaa kuin 29:n lämpökaivon. Vaihtoehtoisesti rivitalot voitaisiin lämmittää esimerkiksi sähkölämmityksellä jos kaukolämpö ei ole enää käytettävissä.

Ehdotus kysynnänhallinnan hyödyntämiseen oli esilämmittää koulurakennusta öisin, minkä vuoksi lämmityksen voisi sammuttaa aamulla. Koska maalämpöä käyttävä lämmitysjärjestelmä käyttää sähköä ja tuntihinnoitellun sähkön hinta on korkeimmillaan aamulla, ehdotus laskisi maksettavan sähkön keskihintaa. Työssä laskettiin, että vuoden aikana esilämmityksen kestosta riippuen noin 100 MWh lämpöä voitaisiin siirtää aamulta yöllä tuotettavaksi, minkä vuoksi vuodessa saatavat säästöt olisivat noin 400 €. Tällaisen kysynnänhallinnan käyttö lisäisi todennäköisesti sähkönkulutusta ja vähentäisi säästöjä, vaikka tätä ei työssä huomioitukaan. Koska arvioidut säästöt ovat hyvin pienet verrattaessa sekä vuotuisiin lämmityskustannuksiin että maalämpöjärjestelmän investointikustannuksiin, ei tutkittu kysynnänhallinnan menetelmä vaikuta hyvin kannattavalta investoinnilta.

Asiasanat: geoterminen energia, keskisyvä maalämpö, kysynnänhallinta

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ABBREVIATIONS

ATES	Aquifer Thermal Energy Storage
BHE	Borehole heat exchanger
BTES	Borehole thermal energy storage
COP	Coefficient of performance
CTES	Cavern thermal energy storage
DHW	Domestic Hot Water
EGS	Enhanced geothermal system
GSHP	Ground source heat pump
LHS	Latent heat storage
NZEB	Nearly zero energy building
ORC	Organic Rankine Cycle
PCM	Phase change material
PTES	Pit thermal energy storage
SHS	Sensible heat storage
SPF	Seasonal performance factor
TCS	Thermochemical storage
TES	Thermal energy storage
TRT	Thermal response test
TTES	Tank thermal energy storage
UTES	Underground thermal energy storage

1 INTRODUCTION

Geothermal energy is a renewable energy source which can be collected from the ground. During the past decades in Finland, geothermal energy has been mostly collected near the surface with boreholes which reach a maximum depth of 300 m. One of the current problems of utilisation of geothermal energy in a larger scale has been the required surface area which is not always available especially in urban areas. This problem can be overcome by constructing deeper boreholes but it has not been often done due to high drilling costs. However, the past two years have shown that there is will to construct deeper boreholes and the first borehole exceeding one kilometre is already in operation (Juuti 2020).

The municipality of Ii, located in northern Finland, is a forerunner in renewable energy and while aiming to become carbon-neutral they are eager to investigate and invest in new technologies which could help them to achieve their goal. Iin Micropolis was interested in the possibility of using a medium-depth borehole, which is 1 – 2 km deep, to heat a new or existing building in Ii. A school, a day-care centre and two terraced houses located in Kuivaniemi in same property were chosen as the study site due to its possible need for new heating system in the future. The buildings are currently using district heating but it has some leakage problems and its renewal is still uncertain and therefore possible heating systems which could replace district heating are investigated. Because of the ambitious emission reduction goals of the municipality of Ii and high investments costs of medium-depth ground source heat pump system (GSHP), demand-side (DSM) management is also considered to be applied at the study site to reduce the energy consumption and operation costs.

The aim of this thesis is to study if a medium-depth borehole could provide enough energy for the study site, the possibility to use demand-side management in a school building, and furthermore if these solutions could be economically feasible. Because there were no medium-depth ground source heat pump systems operating in Finland when this thesis started, only very limited amount of information existed about the subject. Therefore, it is inevitable that rough estimates have to be used in order to evaluate the feasibility of medium-depth ground-source heat pump system at the study site.

In addition to the evaluation of new heating system for the study site, this thesis consists a literature review on current ground source heat pump systems and different energy storage methods. Because the original study site was a new-built swimming hall and indoor ice rink, other energy storage methods besides using a building itself as a thermal storage were considered. Due to the uncertainty considering the construction of planned sports halls, the study site was changed to a school located in Kuivaniemi. The terraced houses were also added to be part of the study site because as well as the school they are also at risk of losing their current heating system in the future.

The research questions of this study were the following:

1. What kind of potential ground source heat pump technologies exist commercially available?
2. Is the medium-depth borehole technology feasible at the study site?
3. What are the advantages and disadvantages of medium-depth ground source heat pump system in terms of investment, operational costs and payback time?
4. What are the opportunities for demand-side management and thermal storage in the school building?

Finally, the objective of the work was to do a sizing study for both medium-depth and regular ground source heat pump systems, and to compare them in terms of benefits, disadvantages and costs.

2 GEOTHERMAL ENERGY

The ground stores energy in the form of heat and it can originate either from the earth's interior or the sun. The heat is formed in the interior by constant radioactive decay, reactions in the molten core and immense pressure which is created by gravitational forces, and it is estimated that the temperature in the core of earth is 3000 – 5000 °C. All heat in the ground is called geothermal energy but the quantities of heat from different sources vary at different depths on the Earth's crust. While heat from the sun is stored close to the surface, heat produced in Earth's interior can be found everywhere and its quantities decrease towards the surface. However, some specific areas in the Earth's crust contain also high-temperature energy and for example in Iceland hot water or steam can be directly used in space heating by transporting the hot fluid to buildings through pipes. To avoid confusion, the low-temperature heat found in the shallow surface and originated from the sun and from the Earth's interior in barely noticeable quantities is called ground source heat. (Banks 2012, p. 11-12; Omer 2008; Huusko et al. 2015)

Earth can be divided into core, mantle and crust based on their chemical properties. Crust can be further divided into continental and oceanic crust, (Lehtinen et al. 1998, p. 25) and core into solid inner and molten outer core. The radius of the earth is approximately 6370 km and the core has a radius of 3470 km of which 40 % is inner core. The mantle is 2900 km thick and the thickness of the crust depends on the location. Oceanic crust is 5 – 8 km while continental crust varies between 15 and 60 km and it can be even bigger under mountain belts. The total heat flow from the earth is estimated to be 44 TW, of which 4 % is from the core, 77 % from the mantle and 19 % from the crust. Core has a low share of heat flow due to its small share of radioactive substances. On the contrary, the crust is only 2 % of the Earth's volume but is more responsible to the heat flow because of the radioactive substances such as uranium found especially in the continental crust. (Banks 2012, p. 16)

The crust and upper part of the mantle form lithosphere which is on top of the more deforming asthenosphere. The boundary is determined based on the mechanical properties and underneath the asthenosphere is mesosphere which is part of the mantle. The thickness of the lithosphere varies typically between 50 and 300 km and it is divided into rigid tectonic plates which move on top of the asthenosphere. There are three types of movements: the plates can move towards each other, move away from one another or slide past each other. Volcanic activity occurs mainly along the lines of tectonic plates and the geothermal heat flux averages around 300 mW/m^2. Therefore, the biggest geothermal resources of the Earth are at these areas. (Lehtinen et al. 1998, p. 25, 74-76; Banks 2012, p. 17-19)

Geothermal energy is a renewable resource and it has several advantages which encourage its usage. Ground stores heat everywhere and therefore geothermal energy is available also in colder climates. In volcanic and seismic areas, the potential is even higher. However, locations with low ground temperature are able to use the same system for both heating and cooling. Geothermal energy systems are secure and they produce heat constantly without relying on weather conditions as solar and wind energy. In addition, unlike wind turbines and solar panels, geothermal energy systems have most of the parts underground and thus are invisible which increases the acceptability of the technology among public. Geothermal energy is also economically viable and the price of energy does not fluctuate much which can be seen as an advantage when compared to for example heating with oil. Furthermore, the systems are compatible with both centralised and distributed energy generation. It is possible to secure space heating fully with geothermal energy system or use other energy sources when heating demand is high. (Rosen & Koohi-Fayegh 2017, p. 2-3; Lauttamäki & Kallio 2013; Motiva 2019b)

Utilization of geothermal energy is not a recent discovery. Based on archaeological evidence it can be estimated that the first use of geothermal energy was already over 10 000 years ago and first geothermal heating system was developed in the 14th century. In addition, hot mineral springs which have been used by ancient people are still in use even if not in such a variety of applications than before. (Rosen & Koohi-Fayegh 2017, p. 1; Olosalo et al. 2016) Today, the main ways to utilize geothermal energy are heating, cooling and electricity generation (Self et al. 2013).

Geothermal energy is divided into shallow and deep geothermal energy. In Finland, the boundary is set around the depth of 300 – 500 m. Shallow geothermal energy can be used for heating and cooling, and deep geothermal energy can also be used in electricity generation. (Uski & Piipponen 2019) In addition, to be more specific, utilisation of geothermal energy approximately at depths of 300 – 2000 m can be called medium-depth geothermal energy (GTK 2018).

2.1 Direct use

Direct use of geothermal energy includes several different applications. Heating and cooling can be provided with or without heat pumps, and the heat is mainly used for space heating, horticulture, industrial processes, bathing, agricultural drying and snow melting. In 2015, geothermal heat pumps were clearly the most used application worldwide with the share of 70 % when comparing the capacity, following with bathing with the share of 13 % and space heating with the share of 11 %. The same year, direct use of geothermal energy provided almost 600 000 TJ of energy. Countries with the highest usage were China, the United States of America, Sweden and Turkey. (Lund et al. 2016; Kananoja et al. 2013)

2.2 Electricity generation

Geothermal energy can be utilised to produce electricity by using steam turbines and it was first done in Italy in 1904. However, it took until 1958 that the technology was commercialised and it was done in New Zealand. Electricity can be produced if a temperature of 85 °C or higher can be collected even though theoretically it is possible to use even lower temperatures. The fluid can be directly injected to the turbine if the dry steam or a mixture of dry steam and brine has a temperature of at least 200 °C. If there is too much water in the fluid, separator might be required to remove it. With lower temperatures, the collected heat can be transferred to another fluid which is used as a working fluid instead. The second fluid needs to vaporise in a lower temperature and therefore for example n-pentane or butane is used. Plants which use a secondary working fluid are called binary systems or organic Rankine cycle (ORC) plants. One of this kind of systems is located in Neustadt-Glewe, Germany where the collected water is 98 °C. (Vélez et al. 2012; Olasolo et al. 2016; Banks 2012, p. 28-29)

2.2.1 Enhanced geothermal systems

Utilisation of geothermal energy to produce electricity is usually done at sites with hydrothermal resources. The drawback is, however, that at some point most of the geothermal fluid has been extracted and the reservoir cannot be utilised anymore. In addition, some sites might not have enough water and steam even before extraction or the permeability might be too low. These sites can have for example poorly fractured hard rocks and they are called hot dry rock reservoirs. They are wanted to be utilised due to their high heat flux which is often caused by the high amount of radioactive substances producing heat. (Banks 2012, p. 32; Olasolo et al. 2016)

In order to utilise these reservoirs, geothermal reservoir with an available fluid to be extracted is created artificially. These systems are called enhanced geothermal systems (EGS) and the first commercial EGS plant which produced electricity in large-scale started operating in 2013 in Australia. The main idea of the system is to drill wells at the site and to increase permeability by creating fractures through which water can flow. During operation, water is injected deep underground where it flows through the hot rocks, collects heat and brings the heat back to the surface where it can be used to generate electricity. (Banks 2012, p. 32; Olasolo et al. 2016)

There are several executed EGS projects around the world. However, all plants are not operating anymore. The first European research project of EGS started in 1987 in Soultz-Sous-Forêts, France and it is still operating. The ground in the area where the plant is operating has unusually high temperatures being around 50 °C at the depth of 400 m. The plant produces both electricity and heat, and the maximum borehole depth is 5 km. In addition, there is Rittershoffen site in the same area which has two wells at the depth of 2,5 km producing heat for industrial use. (Uski & Piipponen 2019; Vallier et al. 2019; Portier et al. 2018)

2.3 Geothermal energy in Finland

Since Finland is not in volcanic area, geothermal energy has not been able to be utilised centuries ago. Ground source heat pumps are the main way of utilization of shallow geothermal energy and they have been used since 1970s in Finland when development of technology has enabled the use of ground source heat. (Juvonen & Lapinlampi 2013) Finland is part of the stable Fennoscandian Shield and the heat flux in Finland varies between 20 and 70 mW/m^2 depending on the location (Pasquale et al. 2001; Kukkonen 1999).

Ground source heat can be utilised everywhere in Finland despite the low temperatures. The surface temperature is prone to seasonal variation and the average temperature is between 2 °C and 7 °C which is warmer than the average air temperature. The ground is warmer in urban areas because buildings have heat leaks and tarmac collects heat due to its darkness. Other factors affecting the surface temperature are for example vegetation and petrophysical properties. Despite the seasonal variation of the surface, the temperature gets stable already at the depth of 15 – 20 m where temperature varies between 2 °C and 10 °C depending on the location. The thermal properties of the bedrock are most affected by the composition and integrity of bedrock and movement of groundwater. (Kananoja et al. 2013; Breilin et al. 2013; Juvonen & Lapinlampi 2013; Huusko et al. 2013)

Temperature rises towards the interior of the Earth. Geothermal gradient presents how much temperature changes with respect to increase of depth of the ground. In Finland, the increase is 0,8 – 1,5 °C for every hundred metres which is low due to the old and stable bedrock of Finland. The value depends on the characteristics of the bed rock such as the share of radioactive compounds. For example, uranium and thorium increase the geothermal gradient by radioactive decay. (Huusko et al. 2013) In southern Finland, temperature at the depth of 1000 m is around 23 °C. In comparison, at the depth of 1000 m the temperature is only between 4 and 12 °C in northern Finland. (Kukkonen 1999; GTK 2018) Depending on the location, 100 °C is reached only at the depth of 6 – 9 km (Uski & Piipponen 2019). The most popular ways to utilise geothermal energy in Finland are presented in figure 1.

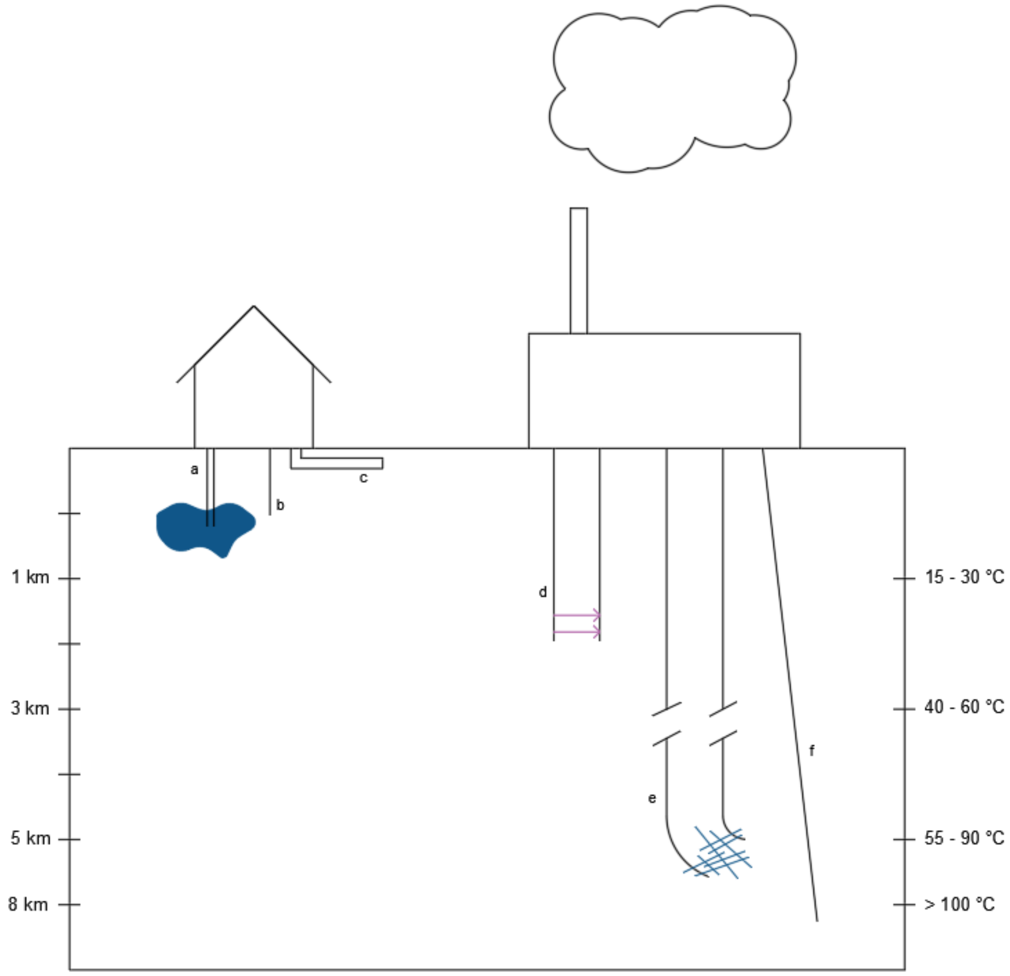

Figure 1. Ways of utilising geothermal energy in Finland, a – groundwater heat pump, b – borehole heat exchanger, c – horizontal ground source heat pump, d – medium-depth geothermal system enhanced with a heat pump and consisting of one or more boreholes, e – enhanced geothermal system, f – deep borehole heat exchanger (modified from Uski & Piipponen 2019).

2.3.1 Medium-depth geothermal energy

The first medium-depth ground source heat pump system in Finland started operating in Espoo in early 2020 providing 60 – 80 % of the energy need of a logistics centre. The borehole is 1300 m deep and after a short operating period it is estimated that it could continuously provide an output of 250 – 300 kW and momentarily an output of 500 kW. Thus, the GSHP system should be able to generate annually over 1000 MWh and its coefficient of performance, which is explained in section 3.3, is 3,5 – 4,5 being slightly higher than the coefficient of performance of conventional boreholes used in Finland. In addition, a second medium-depth GSHP system should start operating in 2020 a year later than it was planned in the initial schedule. This borehole is located in Mänttä-Vilppula at the border of Pirkanmaa and Central Finland and has a depth of 1500 m. Its output and production rate are estimated to be near the same values than the estimations of the first borehole in Espoo. (Juuti 2020; Niemi 2020)

2.3.2 Deep geothermal energy

A power plant which uses deep geothermal energy is under construction in Espoo in Finland (St1). The plant is estimated to start operating during spring 2020 and will replace heat which was produced with natural gas and coal. Geothermal plants are also planned to be constructed in Turku, Tampere and another in Espoo. (Pajunen 2019) The plan in the site which is under construction in Espoo is to drill two boreholes with a depth of approximately 6,5 km. From the first borehole, water is pumped down to the bedrock and water is pumped back to the surface through the second borehole at the temperature of 120 °C. The gained heat is utilised in district heating network in Espoo where the operating company has estimated to cover 10 % of the energy demand. The biggest challenges of the project are drilling due to the hard and granitic bedrock and to succeed to generate water flow between the boreholes. There were several drilling methods used, including water hydraulic hammer drilling, traditional rotary drilling, and air hammer drilling which was used until the depth of 4,5 km. To determine the ending point of the second borehole, stimulation and geophones were used to assess the flow of the water in the bedrock. (St1 2019)

Drilling of the borehole in Espoo did not cause seismic activity but when water was injected with a high pressure to the first borehole of the new power plant, it caused noises and vibrations which were noticed above ground. There have been over 5000 detected seismic activities in 5 km radius from the site and the biggest earthquake caused was 1,9 magnitudes. While constructing a similar plant in Basel, in Switzerland, earthquake with a magnitude of 3,4 was detected and even buildings were damaged by it. Therefore, the construction of the plant was decided to be stopped. However, the water was pumped with a different method in Switzerland and the bedrock is more active than in Finland which means that similar earthquakes which were detected in Switzerland are unlikely to occur in Finland. (Uski & Piipponen 2019; Pajunen 2019)

3 GROUND SOURCE HEAT PUMPS

Ground source heat pumps offer an environmentally friendly way of heating and cooling of buildings. GSHPs are the most common method of direct utilisation of geothermal energy and they utilize heat stored in the ground or water deposits by transferring the heat above ground and into the buildings. Unlike many other heating methods, GSHPs are based on transferring heat instead of creating it. This reduces emissions such as flue gases and smoke which are released in conventional incineration processes used to produce heat. Usage of GSHPs does not require geothermal energy produced deep in the Earth's interior but it can be utilised with deeper GSHPs. (Omer 2008; Lund et al. 2011)

Conventional GSHPs consist of heat pump, distribution system and heat exchanger which can also be called ground loop. The ground loop which often consists of black polyethylene pipe is placed in water, soil or bedrock depending on where the heat is collected. GSHPs are usually divided into closed and open loop systems and loops themselves further into horizontal and vertical. Vertical systems are often referred also as borehole heat exchanger (BHE). Besides vertical and horizontal systems, it is also possible to add heat exchangers to foundation piles. (Juvonen & Lapinlampi 2013; Breilin et al. 2013; Majuri 2018)

Heat energy moves naturally from warm to cold (Omer 2008). The average indoor temperature is around 20 °C while the temperature in the ground where heat is collected is lower. In order to be able to heat buildings with ground source heat, heat pumps are required. (Banks 2012, p. 79-81) Heat pumps are based on reversing the natural flow of heat and thermal effect can be produced by using drive energy. In case of GSHPs, the energy is produced with an electro-compressor which uses electrical energy and the heat is mainly collected from the ground or in some cases from water. Heat pumps with other applications can also use mechanical energy, thermo-mechanical energy, thermal energy or thermo-electrical energy, and the source of heat can be any substance such as air or process gases. (Sarbu & Sebarchievici 2014) Heat pumps used in GSHPs have the same principle as the ones found in refrigerators and even though the operation of GSHPs requires electricity, the gained energy is higher than the utilised. (Kananoja et al. 2013)

Main parts of a heat pump are evaporator, compressor, condenser and expansion valve (Motiva 2019b) which are presented in figure 2. If the GSHP is used for cooling, the system has also a reversing valve which changes the direction of the refrigerant flow and turns the evaporator into condenser and vice versa. In heating mode, the refrigerant of the heat pump, which is mainly liquid, boils and turns into a low pressure vapor in the evaporator due to the heat transfer in the ground loop. The temperature increases slightly in the evaporator and after that the vapor enters the compressor. Compressor uses electrical energy and increases both temperature and pressure of the vapor and at this point the temperature is higher than the temperature inside the building. Therefore, the heat can be transferred in the condenser from the refrigerant to the distribution system (Self et al. 2013) and heat is ultimately used to space heating or pre-heating of domestic hot water (DHW) (Omer 2008). In Finland, the system is connected to hydronic heat distribution being most often underfloor heating in newer buildings or water radiators in older buildings (Majuri 2018). The condenser turns the refrigerant from vapor into liquid but it stays at high pressure and high temperature. At the end of the cycle, the expansion valve decreases the pressure of the refrigerant which also decreases the temperature. (Self et al. 2013)

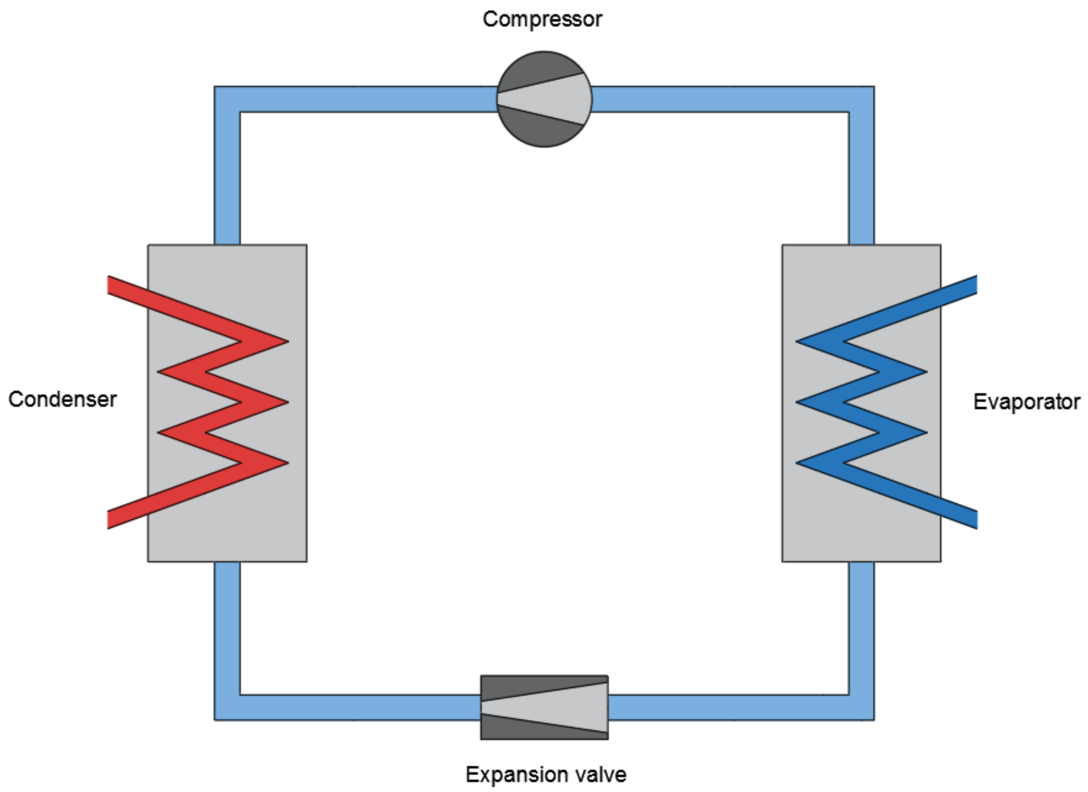

Figure 2. Basic parts of a heat pump (modified from Motiva 2019b).

The technology of GSHPs is suitable for a variety of buildings. In Finland, they are mostly used in detached houses where GSHPs have a share of 13 % of space heating. However, in new-build detached houses the share is almost 60 % and in all buildings around 20 %. (Paiho et al. 2017; Energiauutiset 2016) The amount of GSHPs has started to rise significantly in Finland after 2005 and in 2018 there were over 150 000 of them. The annual increase has been around 8000 during the last years. (Tilastokeskus 2016; SULPU 2019) In Finland, 85 % of all GSHPs are borehole heat exchangers making them clearly the most popular ones (Majuri 2018). When installations are compared to population, Finland has one of the highest installed capacity in the world (Lund et al. 2011). In addition to heating, the low temperature enables cooling without heat pumps in Finland (Huusko et al. 2013).

Even though the smaller buildings are the most common users of the GSHPs in Finland, larger installations are getting more popular. The biggest GSHP energy field is located in southern Finland in a logistics centre and there are 300 BHEs installed which are each 300 m deep. In addition to the most conventional GSHPs, usage of shallow geothermal energy which is collected with construction piles is also increasing. (Lund & Boyd 2016)

3.1 Closed loop systems

Closed loop GSHP systems have heat exchangers underground and they require a carrier fluid which is usually either water or a mixture of water and antifreeze (Sanner et al. 2003). In Finland, the carrier fluid is often denatured water ethanol mixture and it should be able to be used in temperatures between -15 °C and -20 °C. This needs to be considered especially in horizontal systems. (Breilin et al. 2013) However, both medium-depth GSHP systems in Finland use water as a carrier fluid (Juuti 2020). When compared to open loop systems, closed systems offer an advantage of preventing mass transfer between heat carrier fluid and groundwater. It also prevents corrosion and therefore increases the lifetime of the system. (Bär et al. 2015) Both vertical and horizontal closed loop systems have advantages and disadvantages and the better option depends on the case and the conditions at the site (Benli 2013).

3.1.1 Vertical systems

BHEs require drilling of a borehole which has usually a depth of 120 – 300 metres and a width of 105 – 165 mm in Finland (Juvonen & Lapinlampi 2013). Single U-pipe is the most common heat exchanger (Majuri 2018) including two pipes connecting at the bottom. However, it is possible to install even three U-pipes in one borehole or use coaxial pipes. The single U-pipe and coaxial heat exchangers are presented in figure 3. Besides requiring small amount of space, advantages of BHEs include lower landscape disturbance, shorter pipe length and more stable heat production around the year compared to horizontal system (Self et al. 2013; Omer 2008). However, they have higher capital costs (Benli 2013).

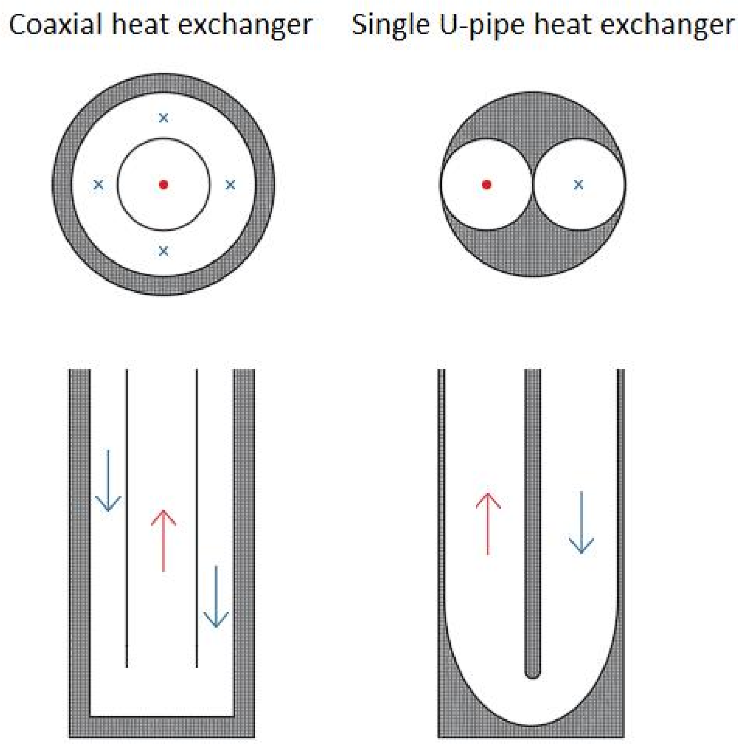

Figure 3. Structures of coaxial and single U-pipe heat exchangers (modified from Śliwa et al. 2018).

Down-the-hole (DTH) is the most economically viable drilling method in Finland due to the characteristics of Finnish bedrock (Majuri 2018). Drilling causes the high capital costs of BHEs and costs are higher in areas with a deep layer of soil. The increase in costs is caused by lower heat conductivity of soil compared to bedrock and required support for borehole while drilling of the stratum. (Huusko et al. 2013) To cut the costs, drilled well which has been used to acquire water from bedrock can be changed into a GSHP system. However, it is often too shallow to get enough energy and another drill might be needed. (Juvonen & Lapinlampi 2013)

In the Nordic countries, the boreholes are drilled into bedrock and they usually get naturally filled with water. Besides avoiding manual filling of the borehole, an advantage of having groundwater is that its movement increases the heat transfer but drilling must be done carefully in groundwater areas to avoid environmental risks such as mixing of groundwaters of different qualities. However, the risks of deterioration of groundwater quality is very small if execution of the BHE is done properly. Filling of a dry borehole is done with water or with other substances such as bentonite and its purpose is to enhance the heat collection. (Juvonen & Lapinlampi 2013; Majuri 2018; Huusko et al. 2013; Self et al. 2013)

To sustain the energy production for bigger sites, the required area increases and it can be hard to find especially in densely populated areas. Upscaling of BHEs can be done by increasing the number of boreholes or drilling deeper boreholes. Increasing the depth increases significantly heat load which the BHE can sustain and even though required pump effect increases with deeper BHEs, the positives outcome the negatives and the pressure drop can be compensated with wider borehole. Holmberg et al. (2016) estimated that if a conventional BHE with a U-tube and depth of 300 m and an 800 m deep coaxial BHE are compared, over 6 conventional BHEs are required to provide an equal heat load which the deep BHE can provide. Therefore, deeper installations are suitable especially in urban areas and the lack of space has been a driver in Norway and Sweden where deeper boreholes with a depth of 400 – 500 m are being constructed commercially even though they are more expensive than the conventional BHE systems. (Holmberg et al. 2016) However, due to the advances of drilling technology, economic feasibility of deeper boreholes has started to increase (GTK 2018).

Because the temperature increases towards the centre of the Earth, potential for heating also increases. On the contrary, potential for cooling decreases and therefore deeper boreholes suit best for buildings with high heating demand and low cooling demand especially at areas with higher ground temperature. If deeper than conventional boreholes are executed, the flow rate and flow area of the heat carrier should be increased. Therefore, coaxial collector suits better than U-pipe due to its larger flow area. (Holmberg et al. 2016) In coaxial BHE, heat carrier fluid can flow two different ways. First way is that the fluid goes down through the inner pipe and flows upwards through the annular space. Second way is reversed and it is the better option for heat extraction. (Liu et al. 2019)

3.1.2 Horizontal systems

Horizontal systems collect heat from the soil near the surface and even the smallest systems in Finland have a ground loop with a length of at least 500 metres. Installation of these systems includes removal of the soil, the actual installation of the collector in the ground and lastly backfilling of the soil. This installation method has usually lower capital costs than drilling of a borehole but horizontal systems also have some disadvantages. Because the ground loop is not deep underground, there is more seasonal variation in the soil temperature at the depth where the collectors are installed. The system has also a lower efficiency due to higher required amount of antifreeze solution which increases the electrical energy demand. This is caused by the increase of the solution viscosity and therefore pumping requires more energy. In addition, horizontal system requires a lot of area, around 1.5 m^2 for every metre of pipe and therefore is not suitable to be installed everywhere. If the soil is dry, the required area can be even larger. (Juvonen & Lapinlampi 2013; Omer 2008)

Horizontal systems can have different types of heat exchangers such as linear pipe, spiral and trench collectors but only linear pipes are used in Finland. In spiral loop, the pipe is looped in trenches horizontally. The disadvantage of this style is greater demand in pipe length but it requires less area than conventional horizontal style and it might also be cheaper. Moreover, backfilling can be even more difficult especially with certain soil types. (Omer 2008; Majuri 2018)

3.2 Open loop systems

Open loop systems use water which is available in nature instead of having a closed loop with an added carrier fluid. They are rarely used in Finland and it is possible to use either ground or surface water as a carrier fluid which is pumped to the buildings. Surface water is released back to where it was taken and groundwater can be released either back to where it was pumped from or to surface waters. In Finland, surface waters are mostly used near lakes or the Baltic Sea. The pipes should be installed near the shoreline but the depth needs to be considered carefully to avoid freezing and breaking of pipes. (Majuri 2018; Juvonen & Lapinlampi 2013; Motiva 2019b)

In Finland, groundwater temperature varies around 4 – 14 °C and in urban areas the temperature is higher than in areas which are in their natural state. The temperature increases close to the city centres resulting in increase of 50 – 60 % in the peak heating load. On the contrary, cooling with groundwater has a lower potential in urban areas. Despite the lower cooling loads, cooling is still a viable option in Finnish urban areas because the groundwater stays below the air temperatures during summer. (Arola & Korkka-Niemi 2014) The highest potential for using groundwater as a heat source in

Finland is in the southern parts. However, there are usable aquifers around the country and theoretically they could provide heating for 25 – 40 % of all residential buildings. (Arola et al. 2014)

3.3 Sizing

When planning a GSHP system, there are several factors which need to be considered. First, the energy need of the site needs to be assessed. The system suits the best if both heating and cooling is needed equally but that is rare in Finland. In addition, the energy demand needs to be high enough to make the system profitable and because GSHPs provide energy steadily, it is also preferred that the energy need is stable. (Lauttamäki & Kallio 2013; Breilin et al. 2013)

It is important to consider if the whole energy need is wanted to cover with the GSHP system. If the system does not cover the full demand and therefore the heat is not sufficient during the coldest times of the year, the surplus energy can be produced with for example electricity or wood. (Juvonen & Lapinlampi 2013) However, it must be noted that in new buildings this requires investing in secondary technology and it might demand additional infrastructure (Banks 2012). Arola et al. (2016) have studied that 97,5 – 98,5 % of the heating energy can be covered if the system has been designed to cover 50 – 60 % of the peak design power and the study was considering buildings in Finland using an open loop system. According to Motiva (2019b), the coverage of 60 – 80 % of the peak power covers approximately 95 % of the total heating energy consumption. In addition, Holopainen et al. (2010) studied that covering 50 % of the peak design power has the lowest lifetime costs for a heat pump system in a Finnish apartment building. In the Nordic countries, systems are designed to provide base load and in Sweden the GSHPs commonly operate 3200 – 4000 hours annually compared to only around 2000 hours in central Europe and also in the USA where the systems are often used for cooling in the southern states (Juvonen & Lapinlampi 2013; Banks 2012, p. 158; Lund et al. 2011).

Besides the energy need, the place for the GSHP must be determined and assessed. Location of the borehole is usually determined by the distance and possibility to have pipes connected to the building. Utilisation of ground source heat might not be a viable option if distances are over 200 – 300 m. However, if the distance from borehole to heat pump is long, that part of the pipe can also be used to collect heat if it is left without insulation. In addition, regulations or zoning might prevent the installation in certain places. For example, the pipes or other GSHP systems nearby complicate the placement. If these are not preventing the use of the decided location, the ground characteristics have to be assessed and determined if the area provides enough energy. (Lauttamäki & Kallio 2013; Juvonen & Lapinlampi 2013)

Ground characteristics, which include for example composition, soil depth, temperature, moisture content, and particle size and shape, have a significant impact on the viability of the GSHP system because thermal conductivity varies between different rock types and drilling of certain types is more challenging than drilling of others. In addition to the ground characteristics, there are several factors affecting the system operation such as diameter of the borehole, distance from the ground loop to the building, depth where pipes are surrounded by water, refrigerant, groundwater and its movement. Some of the most important parameters to be acquired during the sizing procedure are ground temperature, geothermal gradient, thermal conductivity and volumetric heat capacity of ground. (Breilin et al. 2013; Juvonen & Lapinlampi 2013; Sanner et al. 2003)

Thermal conductivity and volumetric heat capacity can be acquired with in situ field tests, laboratory testing or by using values found in literature. Laboratory testing uses solid samples which can be examined with different methods, such as transient method or use of Fourier's law, and many literature values are based on laboratory testing. However, laboratory testing uses only small samples while the area which is examined is a lot larger and it does not either consider groundwater flow. In order to get a more reliable result, thermal response test (TRT) is used. TRT is a field test which can be used to determine needed parameters and it is done by drilling a borehole and injecting heat to a carrier fluid with an electric resistance element or gas burner. During TRT, heat is measured when the fluid enters and leaves the borehole and the collected values are used to determine thermogeological parameters. (Banks 2012, p. 410-417)

In Finland, the cooling period is rather short compared to the heating need due to the cold climate. Therefore, the ground will get colder after years of usage and this needs to be considered in the design and sizing processes especially when there are several boreholes. In case of an undersized system, the ground loop is too short and it leads to a situation where the ground gets too cold. On the contrary, oversized system does not have a significant impact on the ground temperature but it increases the capital costs. (Breilin et al. 2013) In addition, an undersized system may cause freezing of groundwater which is in the borehole and it has higher chances of occurring in the northern parts of Finland because of the colder climate (Huusko et al. 2013).

The performance of GSHP is described with coefficient of performance (COP) which is the ratio of heat energy output and purchased electricity which is used to operate the heat pump. In Finland, the value is approximately 3 (Juvonen & Lapinlampi 2013) and it depends on several factors such as ground characteristics and climate (Self et al. 2013). When the GSHP is used for heating, equation (1) can be used to calculate the COP. In a GSHP system, electrical energy is consumed by the heat pump and water pump, and therefore the total input power is the sum of the consumption of both devices. (Qi et al. 2019)

$$COP_{sys} = \frac{Q_c}{W_{in,total}} \tag{1}$$

In which, COP_{sys} is coefficient of performance of the system

Q_c is heat transfer in the condenser

$W_{in,total}$ is total input power

When comparing the COP of different GSHPs, it is important to take into account the conditions during the measurements. Because the conditions affect the result, it might be better to describe the system performance with seasonal performance factor (SPF) (Juvonen & Lapinlampi 2013) which can be calculated with equation (2). When the season is determined as a full year, it gives the best result by considering all conditions. SPF can be determined with or without including the distribution pump and its inclusion in the calculation results in lower value of SPF but it gives more realistic value by assessing the whole operation of the system. (Stafford & Lilley 2012)

$$SPF = \frac{Q}{E} \tag{2}$$

In which, SPF is seasonal performance factor

Q is total heat output

E is total electrical consumption of a determined season

4 THERMAL ENERGY STORAGE

Thermal energy storage (TES) is used to improve the operation of energy systems and increase the utilisation of renewable energy sources. The issues caused by energy production which does not match the demand can be decreased with use of TES and it can improve the reliability of energy systems. (Sharma et al. 2009) In addition, the use of TES enables to shift energy purchases to times where the costs are lower (Dincer 2002). There are several sources of heat which can be stored by using TES including renewables, combined heat and power, and waste heat generated in industrial processes (Rapantova et al. 2016). Different methods to store thermal energy are divided into sensible thermal storage (SHS), latent thermal storage (LHS) and thermochemical storage (TCS) (Elias & Stathopoulos 2019).

Besides using TES for heating purposes, it can be used for cooling and electricity generation. Electricity can be generated by using the heat to generate steam but the energy is more efficiently used if the heat is directly used for example in space heating. Cooling can be done by coupling TES with air-conditioning or cooling system of the building. (Elias & Stathopoulos 2019; Dincer 2002) In addition, cold thermal storage using LHS method is already applied in several applications such as refrigerated transport (Xu et al. 2019).

The division of TES can also be based on the duration of the storage. Compared to short-term storage, seasonal storage has higher capital costs and causes more challenges but it can provide significantly larger share of annual heat demand. (Giordano et al. 2016) Seasonal storage is used when the energy generation and demand do not match during different seasons. During summer, the space heating demand is low and therefore there is excess thermal energy available. On the contrary, there is a high space heating demand during the winter and in order to match the high demand expensive fossil fuels are used. Nevertheless, if the excess energy during summer is stored, it can be utilised when heating is needed and therefore it is possible to avoid the use of expensive fossil fuels which are usually used during seasonal peaks. (Kandiah & Lightstone 2016; Réveillère et al. 2013)

4.1 Sensible thermal storage

Sensible thermal storage is based on increasing or decreasing the temperature of the storage medium which is either solid or liquid. The SHS systems can be used for both short-term and long-term storage but they have low energy density and there are losses of thermal energy at any temperature. The ability to store heat depends on the specific heat capacity of the material. The amount of heat stored in the storage medium can be calculated with equation (4). Water is a good storage medium due to its high specific heat of 4,19 kJ/kg K, availability and low costs. If temperature of over 100 °C is required, water needs to be pressurised which increases the costs significantly. In higher temperatures also oils, salts and metals can be utilised but they have a lower specific heat and some other disadvantages. For example, metals have handling problems, oils might form volatile compounds and salts can cause corrosion. (Elias & Stathopoulos 2019; Sharma et al. 2009; Dincer 2002)

$$Q = mc_p\Delta T \tag{4}$$

In which, Q is stored heat

m is mass of the material

c_p is specific heat of the material

ΔT is temperature rise

Underground thermal energy storage (UTES) can have several storage mediums including the ground itself, aquifer, and water which is confined in tanks. Borehole Thermal Energy Storage (BTES) utilises the ground which is penetrated by boreholes, Aquifer Thermal Energy Storage (ATES) the groundwater, Tank Thermal Energy Storage (TTES) a storage tank, Pit Thermal Energy Storage (PTES) a dug pit filled with water and gravel, and Cavern Thermal Energy Storage (CTES) cavities which are not manually constructed to store thermal energy. UTES is considered to be cheaper and more reliable than latent thermal and thermochemical storage. However, especially BTES and ATES have environmental impacts which need to be considered when designing the storage because a large area of ground or big part of the aquifer are affected. (Giordano et al. 2016; Rapantova et al. 2016; Fleuchaus et al. 2018) Comparison of BTES, ATES, TTES and PTES is presented in table 1.

Table 1. Comparison of different STS methods (Fleuchaus et al. 2018).

	BTES	ATES	TTES/PTES
Storage medium	Ground, groundwater	Groundwater/ sediment	Water, water/gravel
Subsurface requirements	Moderate	High	Low
Required pre-investigation	Moderate	High	Low
Maximum storage capacity (kwh/m^2)	Low	Moderate	High
Storage volume	Moderate	High	Low
Space requirement	Low	Low	High
Capital costs	Moderate	Low	High
Maintenance	Low	High	Low
Environmental impacts	Moderate	High	Low

4.1.1 Borehole thermal energy storage

BTES is an array of BHEs (Welsch et al. 2018) but unlike conventional BHE system, the BTES system stores heat or cold to the ground (Rapantova et al. 2016). It suits well for long-term storage, which is due to the thermal capacity of the ground and rocks having a low thermal conductivity (Réveillère et al. 2013), and for example solar thermal energy or waste heat from cooling can be utilised (Hirvonen & Sirén 2018). In addition, an advantage of BTES is its suitability to different areas because it does not require an aquifer or special geological structures to be applied. However, the groundwater flow should be negligible to avoid thermal losses. (Bär et al. 2015) Even though BTES has high capital costs, the system has relatively cheap when comparing the costs to the storage capacity and other TES methods (Welsch et al. 2018).

To estimate the storage capacity and temperature, groundwater level and thermal conductivity of ground need to be assessed (Rehman et al. 2018). The heat can be extracted from the storage with or without heat pumps depending on the temperature. If the temperature is 40 – 80 °C, the heat can be extracted directly and with lower temperatures heat pumps are required. The efficiency of conventional BTES can be up to 70 % due to ground having a low thermal conductivity. (Nguyen et al. 2017) However, with medium-depth BTES, which are rarer, the efficiency can be more than 80 %. Because the depth increases, so does the temperature and therefore heat pump might not be required which further decreases the electricity usage. In addition, medium deep BTES have similar advantages and disadvantages than medium-depth GSHP systems, including small area requirements and higher drilling costs. (Welsch et al. 2018; Bär et al. 2015)

BTES is seen as an attractive method to store especially solar thermal energy for larger communities. In Canada, Drake Landing Solar Community, which was built in 2006 and uses BTES, achieved to cover 97 % of the heating demand with solar energy. (Rad et al. 2017) In addition, Hirvonen et al. (2017) have simulated that also in Finnish conditions it is possible to cover 95 % of the energy demand of a 100-house community with solar energy with the use of BTES system. However, the capital costs were almost 50 000 € for a house but they can be decreased to 30 000 € and still achieve to cover 80 % of the heating demand with solar energy.

4.1.2 Aquifer thermal energy storage

ATES has been first time experimented reportedly in the USA in 1976. It is based on using groundwater heat pump for heating or cooling and at the same time storing heat or cold into the aquifer. Cold water is extracted from the aquifer and heated with the excess heat during summer before injecting it back to the aquifer. In the winter, the heated water is extracted and used directly. Besides using it in space heating, it has also been proposed to use other sources of heat such as waste heat or solar thermal energy (Réveillère et al. 2013; De Schepper et al. 2019).

ATES is most suitable for long-term storage (Dincer 2002) and for buildings which require both heating and cooling. In addition, it is often used in larger buildings such as offices or hotels. (Pellegrini et al. 2019) The advantage of ATES is its suitability to urban environments due to small space requirements. However, several sites have experienced some issues such as corrosion and clogging. (Réveillère et al. 2013) Nevertheless, there are over 2800 ATES systems operating. Over 80 % of them are in the Netherlands and around 10 % in Sweden, Denmark and Belgium. Almost all systems are low-temperature systems having a storage temperature of less than 25 °C. (Fleuchaus et al. 2018)

4.2 Latent thermal storage

In latent thermal storage, energy is stored by causing a phase transformation. Besides solid-liquid, liquid-gas and solid-gas transformations, LTS is also able to utilise solid-solid transformation in materials in which changes in crystalline structure occur. However, liquid-gas and solid-gas transformations are more challenging due to a large volume change. LTS utilises materials which have a narrow temperature window where the phase change occurs. The materials are called phase change materials (PCM) and their classification is presented in figure 4. Economic, thermal, physical, kinetic and chemical properties must be considered when choosing a suitable PCM. These properties include for example abundance, small volume change, safety and a suitable phase change temperature which is dependant on the application. (Elias & Stathopoulos 2019; Sharma et al. 2009)

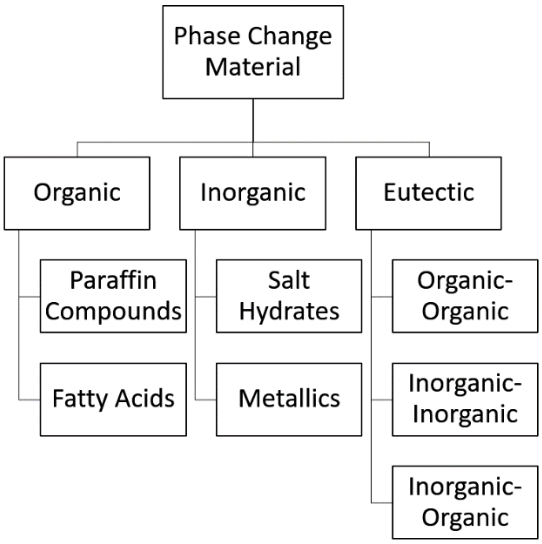

Figure 4. Different phase change materials (modified from Zhou et al. 2012 and Sharma et al. 2009).

To enhance energy conservation and to reduce temperature changes in buildings, PCMs can be incorporated into building structures. It is possible to add liquid or powdered PCMs directly into building materials or dip them into melted PCMs which is absorbed into internal pores. Both direct incorporation and immersion can be used for example with gypsum and concrete but they might have leaking problems. The leaking can be avoided with encapsulation which is based on adding PCMs into a container. Different encapsulation methods can be divided into macroencapsulation and microencapsulation. While microencapsulation uses containers such as tubes or spheres which are hard to incorporate into structures and have low thermal conductivity, microencapsulation uses sealed polymeric films which are easier and cheaper to utilise in buildings. (Zhou et al. 2012) However, there are still problem with compatibility of the plastic and organic PCMs (Elias & Stathopoulos 2019).

Encapsulation seems to be the most promising method to use PCMs in buildings but the barrier is the temperature variation between different seasons and therefore the PCMs might not be able to be utilised around the year. To overcome this barrier, it has been proposed to use two PCMs but the efficiency is decreased due the heat transfer between the PCMs. There are several demonstration sites being prepared which are used in the evaluation of the feasibility of PCMs with the use of solar and geothermal energy. (Elias & Stathopoulos 2019) In addition, Araújo et al. (2017) have carried out a study where eight PCMs with different melting temperatures were evaluated in Portuguese residential building. Even though the study showed a total energy reduction of 13 %, the use of PCM in building materials was still not economically feasible. Furthermore, it has been proposed by Bottarelli et al. (2015) to use PCMs to improve the COP of horizontal GSHP systems by reducing the seasonal variation of ground temperature which would result in colder ground during summers and warmer ground during winters. This would enable the use of UTES also in horizontal systems beside BHEs even though it is often believed that due to higher seasonal variation UTES is not possible in shallow ground.

4.3 Thermochemical storage

Thermochemical storage is based on chemical reactions and molecular bonds which are broken and reformed. The method requires a reversible chemical reaction which demands energy in one reaction and releases it during the reverse reaction. Despite TCS having the highest energy density when comparing to SHS and LTS, it still requires research due to several challenges. (Elias & Stathopoulos 2019; Sharma et al. 2009) One of the most important challenges is to find suitable materials which fulfil several requirements. The most optimal materials have high chemical conversion rates, complete reaction reversibility, high reaction enthalpy, fast reaction kinetics in both reactions and reaction temperatures around 400 – 1200 °C. In addition, the material should be safe, abundant and there should not be any side reactions which produce by-products. (André & Abanades 2018)

4.4 Demand-side management

Demand-side management is a method to level the peaks in energy generation and to enhance the use of renewables by increasing the flexibility of energy demand. DSM has already been introduced in detail in 1980s and it has several objectives which are presented in figure 5. DSM has also four different strategies which are energy efficiency, time of use, demand response and spinning reserve, and multiple of them are required to be used simultaneously in order to make DSM work effectively. (Hirmiz et al. 2019; Palensky & Dietrich 2011; Gellings & Smith 1989) According to Lizana et al. (2018), DSM is seen as a promising method to increase sustainability despite the increase in energy usage by using DSM with technologies which are able to predict the most favourable times to use energy storage by considering the future electricity prices and environmental issues. Besides reducing costs and potential to increase environmental benefits, use of demand-side management can also reduce the need of reinforcing the energy infrastructure.

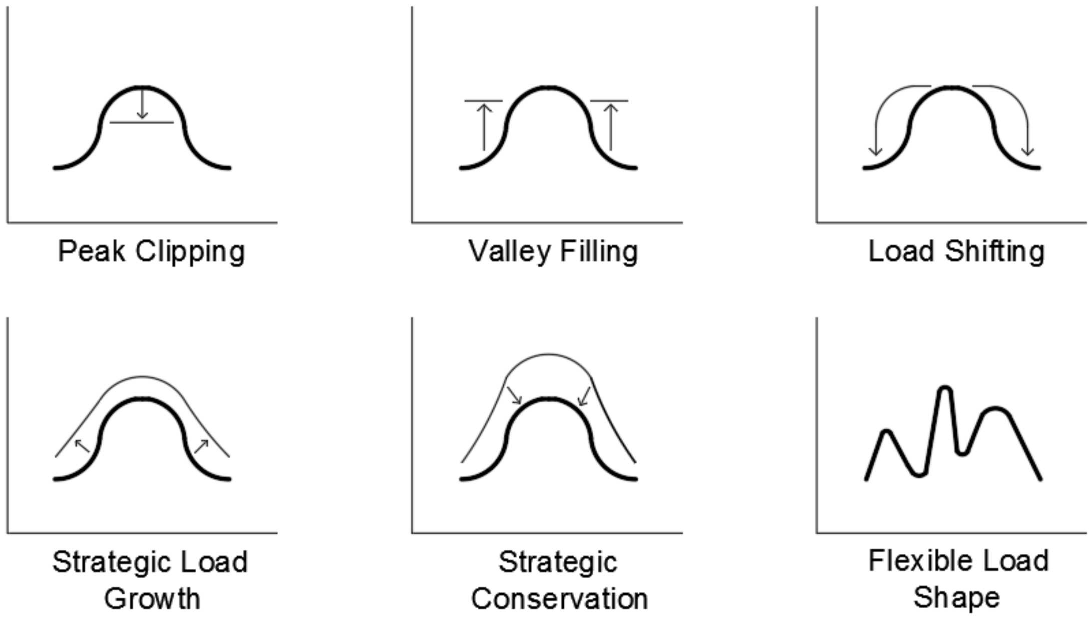

Figure 5. Objectives of demand-side management (modified from Gellings & Smith 1989).

In cold climates, heating of buildings utilises a large portion of the produced energy and therefore Finnish buildings which especially are using electricity for heating are suitable users of TES. It can be utilised by consumers to store energy during off-peak periods and the storage can be discharged during on-peak periods when the GHG emissions of the grid and price of the energy are higher. Due to the increased capital costs caused by TES, energy storage and utilisation should be timed correctly to make DSM profitable. (Hirmiz et al. 2019) Arteconi et al. (2013) have studied DSM with heat pumps and TES, and concluded that even though the coupling of these technologies does not result in significant energy savings, the costs can be cut if the system utilisation timing is based on the electricity rates.

There are several different energy storage methods which can be used in DSM. Besides STS, LTS and TCS, the building itself can be used to store thermal energy or electrical energy can be stored with batteries. (Lizana et al. 2018) They all have their own advantages and while water and PCMs can be used for quick response, boreholes are suitable for cases where large capacity is needed (Hirmiz et al. 2019). The use of the thermal mass of a building offers an advantage of avoiding additional capital costs because the building already exists and thus it can be seen as an attractive option (Romero Rodríguez et al. 2018).

The potential of thermal mass as a storage depends on the occupancy and the thermal capacity of the building envelope (Carvalho et al. 2015). Thermal mass can be utilised with preheating or precooling during off-peak hours but it might have an effect on the thermal comfort and therefore the use of the storage must be done carefully. The heating system can also be turned off during on-peak hours without preheating and it can be turned back on after the on-peak hours or when temperature has decreased to the setpoint temperature. In addition, to increase flexibility, the temperature setpoints can be lowered during on-peak and increased during off-peak. If there are periods when there are no occupancy, the building could even be overheated. However, overheating causes increase in energy utilisation and therefore the consideration of electricity prices is vital and it determines the profitability of this strategy. (Romero Rodríguez et al. 2018) Carvalho et al. (2015) have studied the use of building thermal mass and a GSHP system to increase the flexibility and it is seen as an effective method to decrease operational costs and to shift the peaks.

5 HEATING DEMAND OF BUILDINGS

In 2017, heating of buildings demanded 288 000 TJ of energy in Finland which was 26 % of all utilised energy (Tilastokeskus 2018b). Space heating accounted for 68 % and domestic hot water heating 15 % of the energy usage of households (Tilastokeskus 2018a). The sources of energy utilised for space heating are presented in figure 6. Due to the high energy demand of heating and great potential to increase the energy efficiency, buildings have been concentrated on when aiming to reduce energy usage. However, despite the potential of significant energy reductions, energy usage of building sector requires a long period of time to be decreased because buildings have long lifespans of 50 – 100 years. In Finland, the amount of new buildings is around 1,4 % annually while around 1,0 % is demolished and the buildings are renovated only few times during their lifespan. Therefore, the renewal of building stock is rather slow and the new technologies and improvements in energy efficiency are not implemented as fast as technology develops. (Tuominen et al. 2014)

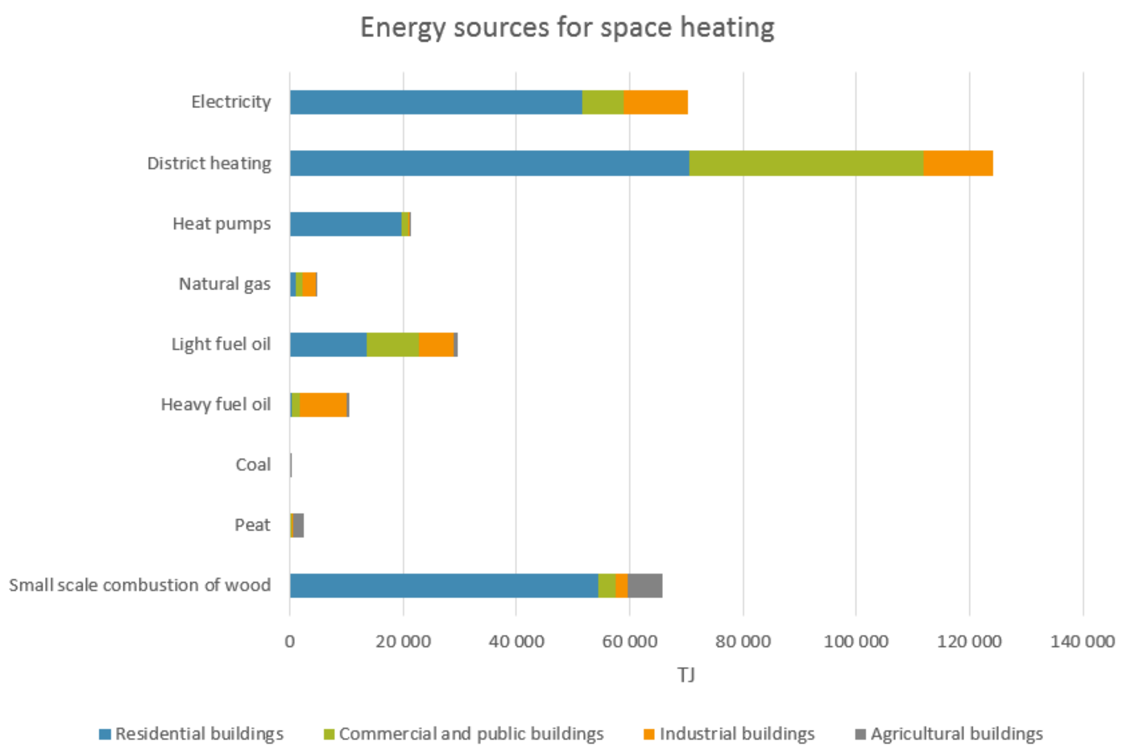

Figure 6. Energy sources used for space heating in Finland in 2016 (Tilastokeskus 2019).

The use of energy for heating purposes is often presented with specific consumption of heating energy in terms of building area or volume. If the specific energy consumptions of different years are compared, the values should be weather-adjusted. The annual specific heating consumptions of different building types in Finland in 2006 are presented in table 2 where it can be seen that the use of the building has a significant impact on the heating consumption and on average residential buildings have higher specific heating consumption than public buildings. Due to the differences of buildings, they are divided into different categories presented in table 3. It should be noted that the heating energy consumption increases towards the northern part of Finland and for example apartment buildings and terraced houses built in southern Finland in 1960 – 1980 have an annual specific heating consumption of 45 – 65 kWh/m^3 while similar buildings in central Finland have 10 – 15 % and in northern Finland 25 – 30 % higher heating energy consumption. (Virta & Pylsy 2011; Sektoritutkimuksen neuvottelukunta 2008)

Table 2. Weather-adjusted annual specific heating consumption of different Finnish buildings in 2006 (Sektoritutkimuksen neuvottelukunta 2008).

Building type	Weather-adjusted specific heating consumption (kWh/m^3)
Residential buildings	61,6
Buildings for institutional care	70
Office buildings	46,1
Assembly buildings	37,5
Educational buildings	45,5
Warehouses	48,7
Transport and communications buildings	30,7
Shelters	24,2
Other buildings	43,1

Table 3. Classification of buildings (Decree of the Ministry of the Environment on the Energy Performance of New Buildings 1010/2017).

Category	Buildings
1	Small residential buildings a) Detached houses and link-detached houses with a net heated area (A_{net}) of 50–150 m^2 b) Detached houses and link-detached houses with a net heated area (A_{net}) exceeding 150 m^2 but not exceeding 600 m^2 c) Detached houses and link-detached houses with a net heated area (A_{net}) exceeding 600 m^2 d) Terraced houses and blocks of flats with residential stories on a maximum of two stories
2	Apartment buildings (at least 3 stories)
3	Office buildings, health care centres
4	Commercial buildings, department stores, shopping centres, wholesale and retail trade buildings (excluding grocery trade units under 2000 m^2), shopping halls, theatres, opera, concert and congress halls, cinemas, libraries, archives, museums, art galleries, exhibition halls
5	Accommodation establishment buildings, hotels, boarding houses, residential building for communities, retirement homes, residential care institutions
6	Educational buildings, day-care centres
7	Building for sports and physical activities excluding indoor ice rink and indoor swimming pool
8	Hospitals
9	Other buildings, warehouses, transport and communication buildings, indoor ice rinks, indoor swimming pools, grocery trade units under 2000 m^2, portable buildings

European Union regulates that buildings should be shifted towards nearly zero energy buildings (nZEBs) which are defined as “a building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby”. (European Union 2010) Finnish buildings have been improving in energy efficiency for decades. The biggest improvements have been in new buildings built after 2010 due to stricter policy in thermal insulation. For example, around 30 % of public and commercial buildings built in 2001 – 2010 achieved an energy efficiency rating of C or higher and the same rating was achieved by around 90 % similar buildings built after 2010. (Ympäristöministeriö 2017) The E-value ratings of some building types are presented in table 4.

Table 4. E-value ratings of different buildings and E-value presented as kWh_E/m^2year (Decree of the Ministry of the Environment on Energy Performance Certificates of Buildings 1048/2017).

Rating	Category 1d	Category 2	Category 3	Category 4	Category 6
A	$E \leq 80$	$E \leq 75$	$E \leq 80$	$E \leq 90$	$E \leq 90$
B	$81 \leq E \leq 110$	$76 \leq E \leq 100$	$81 \leq E \leq 120$	$91 \leq E \leq 170$	$91 \leq E \leq 130$
C	$111 \leq E \leq 150$	$101 \leq E \leq 130$	$121 \leq E \leq 170$	$171 \leq E \leq 240$	$131 \leq E \leq 170$
D	$151 \leq E \leq 210$	$131 \leq E \leq 160$	$171 \leq E \leq 200$	$241 \leq E \leq 280$	$171 \leq E \leq 230$
E	$211 \leq E \leq 340$	$161 \leq E \leq 190$	$201 \leq E \leq 240$	$281 \leq E \leq 340$	$231 \leq E \leq 300$
F	$341 \leq E \leq 410$	$191 \leq E \leq 240$	$241 \leq E \leq 300$	$341 \leq E \leq 390$	$301 \leq E \leq 360$
G	$411 \leq E$	$241 \leq E$	$301 \leq E$	$391 \leq E$	$281 \leq E$

Reda & Fatima (2019) have studied how apartment buildings can achieve the energy efficiency targets in Finland. The apartment building achieves the nZEB requirements for example if district heating is used as the main source of heat and Finnish passive house standards are adopted, or GSHP system is used as the main source of heat and either energy efficient or passive design standards are adopted. In addition, on-site solar energy installations are seen as a positive way to reach the requirements. In addition, a study conducted by Paiho et al. (2017) concluded that both detached house and apartment building which were aiming to nZEB requirements had the lowest life-cycle costs when GSHP systems were used. The study compared different heat pump systems and utilisation of solar energy for both buildings, and also district heating for apartment building.

5.1 Calculation of heating demand

In order to calculate the heating demand of a building, there are several parameters which are required to be taken into account. The weather conditions have a significant effect on the heating load and energy performance. (Rosen & Koohi-Fayegh 2017, p. 96-97) The difference between outdoor and indoor temperature and thermal conductance of the building determine the rate of heat loss from the building and the heat loss can be defined with equation (3). When there is a high temperature difference the building requires more heating energy but the demand can be decreased with a low thermal conductance. (Banks 2012, p. 151) In addition to the heat loss from the outer surface of the building, the ventilation causes heat losses (Motiva 2016).

$$Q \approx \Delta\theta \times U \tag{3}$$

In which, Q is rate of heat loss in watts

$\Delta\theta$ is temperature difference

U is thermal conductance

Besides heat losses, the heating demand depends also on heat gains which can be divided into envelope and internal heat gains. Envelope gains are caused by an outdoor temperature which is higher than indoor temperature or solar radiation, and internal heat gains by several factors such as people, lighting and appliances. (Catalina et al. 2013) The annual internal heat gains can be calculated with formula 4 and with the use of table 5 (Decree of the Ministry of the Environment on the Energy Performance of New Buildings 1010/2017).

$$Q = kP\frac{\tau_d}{24}\frac{\tau_w}{7}\frac{8760}{1000} \tag{4}$$

In which, Q is annual thermal load (W)

k is the average usage of lighting and appliances, and occupancy rate during the period of building's occupancy

P is the thermal load

τ_d is the number of hours of building occupancy per day

τ_w is the number of hours of building occupancy per week

Table 5. Occupancy periods and internal thermal loads of different buildings (Decree of the Ministry of the Environment on the Energy Performance of New Buildings 1010/2017).

Category	Time	Occupancy period		Usage/occupancy rate	Internal thermal load per net heated area (W/m^2)		
		Daily h/24h	Weekly d/7d		Lighting	Consumer equipment	Humans
1	00-24	24	7	lighting 0,10 other 0,60	6	3	2
2	00-24	24	7	lighting 0,10 other 0,60	9	4	3
3	07-18	11	5	0,65	10	12	5
4	08-21	13	6	1	19	1	2
5	00-24	24	7	0,3	11	4	4
6	08-16	8	5	0,6	14	8	14
7	08-22	14	7	0,5	10	0	5
8	00-24	24	7	0,6	7	9	8

Degree day method uses long-term meteorological data to estimate heating energy demand and its variation, and storage requirements (Sarak & Satman 2002). The method is based on the assumption that the energy demand is linear with the temperature difference between indoor and outside temperature. Because DHW heating is not linear with the outdoor temperature, it is not considered in degree day method but its heating demand can be calculated with the use of table 6. (Motiva 2017) In order to calculate degree days, baseline temperature needs to be determined which is the temperature below which heating is required to keep a comfortable indoor temperature and at this temperature the heat losses and gains are approximately balanced. The value depends on several factors such as different sources of heat gains and the utilisation of the building. (Banks 2012, p. 151-152)

Table 6. Annual net heating energy demand for domestic hot water in different buildings (Decree of the Ministry of the Environment on the Energy Performance of New Buildings 1010/2017).

Category	Net heating energy demand for DHW (kWh/m^2a)
1	35
2	35
3	6
4	4
5	40
6	11
7	20
8	30

Calculation of degree days is done by calculating the temperature difference between the average temperature and the baseline temperature (Banks 2012, p. 151). In Finland, the baseline temperature is usually 17 °C. Days which have higher average temperature than 10 °C during the spring or 12 °C during the autumn are not considered because when temperature falls below or exceeds these limits it is assumed that the heating is turned on or off. (Motiva 2017) Annual degree days of different cities of Finland are presented in table 7 and the values are based on data from 1981 – 2010 (Finnish Meteorological Institute 2019). In addition, degree days can be calculated for cooling demand. On the contrary to heating degree days, cooling degree days are calculated by considering the temperatures which exceed certain baseline temperature which can be different from the baseline used for heating degree days. (Banks 2012, p. 152)

Table 7. Degree days of different Finnish cities (Finnish Meteorological Institute 2019).

City	Degree days
Helsinki	3878
Tampere	4424
Vaasa	4469
Jyväskylä	4832
Oulu	5057
Ivalo	6231

Besides the climate, thermal conductance has a significant impact on the energy efficiency and its value depends on the architecture and structure of the building. Some of the most important building structures to be considered are the surfaces of walls, roofs and windows, air change rate, area to volume ratio and placement of windows. Proper insulation of the building envelope decreases heat loss (Catalina et al. 2013) and the thermal resistance of different structures can be presented with U-values (Banks 2012, p. 153). To prevent heat losses, the aim is to reach a low U-value. When comparing detached houses in Finland which have been built before 1960s and requirements for new houses built after 2010, the U-value of outer walls has decreased from 0,69 to 0,17 and of windows from 2,2 to 1,0 over the years. (Tuominen et al. 2014) If heat losses through convection are not considered, equation (3) can be used as a simplified method to calculate the theoretical heating demand by using degree days and calculating the thermal conductance with the help of U-values (Banks 2012, p. 152).

6 REGULATIONS

European Union has an energy strategy which aims to provide the citizens affordable, secure and renewable energy. This is done by several actions such as improving energy efficiency and building an energy grid across Europe. Besides regulations, the aims can be achieved with funding research. (European Commission 2019) European Union funds projects in the area of heating and cooling which aim to reduce energy consumption and increase the use of renewables. These aims are attempted to achieve with projects with wide variety of actions, including decreasing the price of geothermal energy, improving drilling technologies for utilisation of geothermal energy, increasing the utilisation of waste heat and developing thermal storages. (European Union 2016)

6.1 Geothermal energy

According to European Union's directive on the promotion of the use of energy from renewable sources, all member states should increase the share of renewable energy. Each country has their own national target which is having at least a 20 % share of renewable energy sources in gross final energy consumption. Because geothermal energy is renewable energy, its share can be increased to achieve the target. In addition, member states should research the possibility of using geothermal energy in district heating. (European Union 2009) Installations of GSHPs have been subsidized in Finland in the 1980s and 2000s. Nowadays, tax deduction is possible but it only includes labour and not the materials. (Majuri 2016)

In Finland, the Land-use and Building Act requires a permission to be applied for a horizontal or vertical GSHP. Installation to a new building does not require a separate permission but the permission for the system is applied in the same building permission procedure which is done for the new building. If the system is installed to an older building, action permit is applied instead. (City of Oulu 2019) However, few municipalities have a building code which states the system does not require the action permit if the project is assumed to be insignificant (Majuri 2016).

If the installation is in a groundwater area, permit in accordance with the Water Act is needed. The Water Act states that a permission is needed for a project which might change the quality or quantity of groundwater and The Environmental Protection Act prohibits to handle substances or energy in a way it might cause a health risk or reduction in the quality of the groundwater in an important groundwater area. However, there are no strict regulations of the effects such as the permitted temperature change of the groundwater. (Majuri 2016; Juvonen & Lapinlampi 2013)

Health Protection Act does not prohibit the installation of a GSHP system but the act needs to be considered during the sizing process of the system. The act states that the temperature or the humidity of the building may not cause harm to health. If the GSHP heats the water, system must be sized to keep the temperature in an adequate level to prevent microbial growth. In addition, Chemical Act applies to the refrigerants and it requires chemicals to be handled in a way that they do not harm the environment. Depending on the dangerousness and amount of the refrigerant, a permission or a notification might be required. (Juvonen & Lapinlampi 2013)

RES directive (2009/28/EC) states that the member states of the European Union must have available certification or qualification schemes for shallow geothermal system installers. In Finland, there is a 12-day EUCert training which includes the certification scheme coordinated by The European Heat Pump Association and obligatory refrigerant qualification. If the GSHP has less than 3 kg of refrigerant, the EUCert training is adequate but a larger system requires months or years of additional training depending on the person’s earlier studies. In addition, there is a vocational degree program for construction of boreholes but it is not compulsory for the constructors. (Majuri 2016)

Before execution of a BHE, one must make sure there are no restriction of drilling in the planned location of the borehole. In some cities, it is restricted to have a borehole in a groundwater area. In addition, wires, pipes, neighbouring GSHPs or plans to have underground constructions at the location must be considered. Boreholes must be 7,5 m from the boundary of neighbouring property, 15 m from another borehole, 3 m from other heat pipes, buildings or own sewage pipes, 5 m from others’ sewage pipes, and 25 m from tunnels and caves. Furthermore, buildings should not be constructed on top of GSHP systems and the systems need to locate 20 – 50 m from roads depending on the size of the road. (Juvonen & Lapinlampi 2013)

Deep geothermal systems do not have separate regulations and their environmental impacts have not been assessed properly in Finnish geological conditions. The technology is not either considered in several national acts and European Union directives including Directive on industrial emissions (2010/75/EU), Environmental Protection Act

(527/2014) and Act on Environmental Impact Assessment Procedure (252/2017). In addition, there are no BAT or BREF documentation about geothermal energy production made by the European Union. Due to the lack of regulations, deep geothermal systems are not seen as a risk for the environment in all cases. However, it is proposed that these systems are included in different regulations and for example environmental impact assessment should be done and seismicity should be considered. (Uski & Piippo 2019)

6.2 Buildings

Due to the European Union directive (2010/31/EU), new public buildings which are built after 31st of December 2018 and all new buildings which are built after 31st of December 2020 must be NZEBs and have a high energy efficiency. The small amount of energy which is needed should also be covered with renewable energy sources. During the planning process of new buildings, alternative high-efficiency heating and cooling systems, such as heat pumps, should be considered. In addition, if possible, old buildings which undergo major renovation should have improvements which improve the energy performance to the current required level. (European Union 2010) In Finland, there have been energy regulations since 1976 (Ruusala et al. 2018) and half of the floor area of Finnish buildings has been built after the first regulations (Ympäristöministeriö 2017). The most recent regulations on energy efficiency were introduced in 2017 (Decree of the Ministry of the Environment on the Energy Performance of New Buildings 1010/2017).

The designer of a new building must make sure that the energy efficiency is at a required level. The energy efficiency must be determined with E-value or structural energy efficiency. E-value presents the demand for purchased energy which is required in standard use. The energy is weighted by coefficients of different sources of energy presented in table 8 and therefore E-value does not present the actual energy consumption. For new buildings, there are set limits which the E-value may not exceed and the limits are presented in table 9. In addition, table 9 presents values which must be used during the calculation of E-value. (Decree of the Ministry of the Environment on the Energy Performance of New Buildings 1010/2017)

Table 8. Coefficients used in E-value calculation (Government Decree on the numerical values of coefficients for forms of energy used in buildings 788/2017).

Source of energy	Coefficient
Electricity	1,2
District heating	0,5
District cooling	0,28
Fossil fuels	1
Renewable fuels used in the building	0,5

Table 9. Limits for E-value, outdoor air flow, and heating and cooling limits for buildings (Decree of the Ministry of the Environment on the Energy Performance of New Buildings 1010/2017).

Category	Limit for E-value ($kWhE/(m^2a)$)	Outdoor air flow ($dm^3/(sm^2)$)	Heating limit (°C)	Cooling limit (°C)
1	a) 200 – 0,6 A_{net} b) 116 – 0,04 A_{net} c) 92 d) 105	0,4	21	27
2	90	0,5	21	27
3	100	2	21	25
4	135	2	18	25
5	160	2	21	25
6	100	3	21	25
7	100	2	18	25
8	320	4	22	25
9	No limit	Not defined	Not defined	Not defined

The calculation of E-value requires determination of heat losses and it must be done with the values presented in table 10. If structural energy efficiency is used instead of E-value, the energy efficiency may be at least at the same level as it would be if calculation of heat loss was done with the reference values presented also in table 10, and the value of infiltration was set to 0,60 $m^3/(h\ m^2)$ and the value of ventilation heat recovery efficiency to 65 %. In addition, heating must be provided with district heating, ground source heat pump or air-to-water heat pump, and the building must have a mechanical supply and exhaust ventilation system which has a maximum specific fan power of 1,5 $kW/(m^3/s)$. (Decree of the Ministry of the Environment on the Energy Performance of New Buildings 1010/2017)

Table 10. Reference U-values for E-value and structural energy efficiency calculations (Decree of the Ministry of the Environment on the Energy Performance of New Buildings 1010/2017).

Structure	U-value for E-value calculation	U-value for structural energy efficiency calculation
External wall (category 1)	0,17	0,12
External wall (category 2)	0,17	0,14
Floor against outdoor air	0,09	0,07
Floor against crawl space	0,09	0,1
Element against the ground	0,16	0,1
Roof	0,09	0,07
Window	1	0,7
Door	1	0,7

Despite the calculation method of energy efficiency, there are some set limits for new buildings. The infiltration may not exceed 4 $m^3/(h\ m^2)$ except if it is required due to a structure needed for the use of a building, and the specific fan power of a mechanical supply and extract ventilation system is limited to 1,8 $kW/(m^3/s)$ and for a mechanical exhaust ventilation system to 0,9 kW(m3/s). (Decree of the Ministry of the Environment on the Energy Performance of New Buildings 1010/2017) The temperature of acquired domestic hot water must be at least 50 °C but it may not exceed 65 °C. The indoor temperature in households must be between 18 and 26 °C during the heating period and between 18 °C and 32 °C at other times. The temperature is measured approximately at the height of 1,1 m. (Decree of the Ministry of Social Affairs and Health on Health-related Conditions of Housing and Other Residential Buildings and Qualification Requirements for Third-party Experts 545/2015)

The indoor temperature may not exceed cooling limits between June and August for more than 150 degree hours. These cooling limits have been set to be 27 °C for apartment buildings with 3 or more floors and 25 °C for other specified buildings in the decree including education buildings, hotels, hospitals and office buildings. For new buildings which have a set limit for accepted temperature during summer months, the temperature calculation is required. (Decree of the Ministry of the Environment on the Energy Performance of New Buildings 1010/2017) Furthermore, while designing heating of a building, 21 °C must be used as the standard indoor temperature during the heating period (Decree of the Ministry of the Environment on the Indoor Climate and Ventilation of New buildings 1009/2017).

7 EXPERIMENTAL CASE STUDY: KUIVANIEMEN KOULU

The municipality of Ii is part of the HINKU programme which is aiming to decrease greenhouse gas emissions. In order to achieve its reduction goals, the municipality is looking for new technologies which could be applied in both Ii and other cities around Finland. The aim of this study was to investigate the possibility of using medium-depth GSHP system in the municipality of Ii which is located approximately 35 km north from Oulu and had 10 000 inhabitants in 2007 (Tilastokeskus 2019).

Kuivaniemen koulu, which is located in Kuivaniemi 35 km north from the city centre of Ii and shown in figure 7, was chosen as the study site due to its need for new heating system. At the moment, the school is using district heating but the district heating network is old and has leakage problems. The injected water has had to be increased by several percentages of the total volume which leads to a decrease in efficiency. Because the amount of district heating users is low in Kuivaniemi and the renewal has high investment costs, the renewal of district heating network is uncertain. Therefore, the municipality is looking for a substitutive heating method.

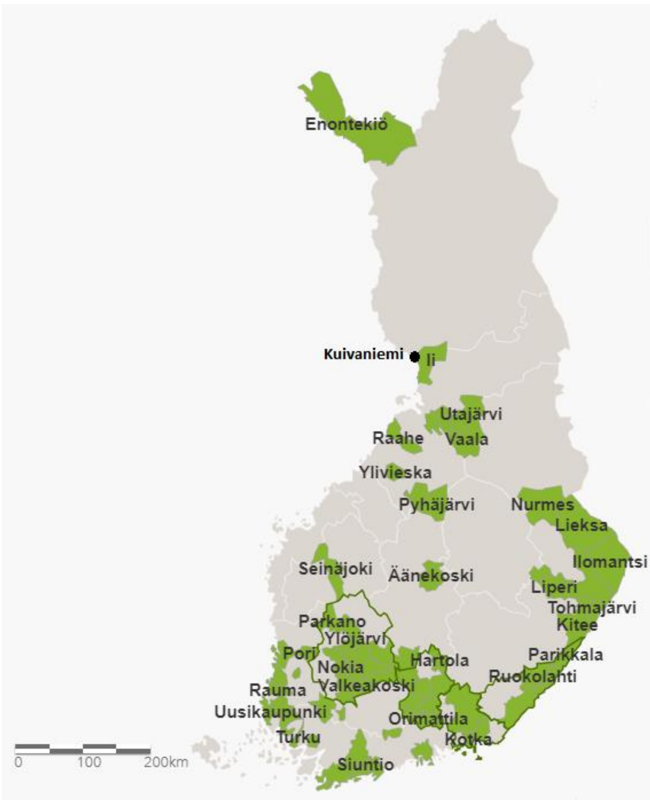

Figure 7. Location of HINKU municipalities and Kuivaniemi where the study site is located at (SYKE 2020b).

7.1 HINKU

HINKU is a network of carbon neutral municipalities in Finland which are frontrunners in deployment of low-carbon solutions and tackling the climate change. The programme was launched in 2008 and originally the network only consisted of five rural municipalities. Today, there are 73 municipalities participating with a total of 1 900 000 inhabitants and the sizes of municipalities varying between 1800 and 238 100 inhabitants. The aim of these municipalities is to decrease 80 % of the greenhouse gas emissions from the level of 2007 by 2030 and the reduction has been 26 % in 2016. In addition, it is important that the municipal officials and politicians should commit to leadership in climate policy. One of the biggest achievements of HINKU is the development of joint purchases of solar panels in Finland. (Lukkarinen et al. 2018; Matschoss & Heiskanen 2017; SYKE 2018; SYKE 2020a)

The municipality of Ii has been a HINKU municipality since 2012. In 2016, Ii had already reduced GHG emissions by 52 % and the changes in the emissions of different sectors are presented in table 11. Most of the reduction is due to increase in wind power capacity and all sectors except agriculture have reduced their emissions. Nevertheless, the municipality has invested in several other technologies enhancing energy efficiency and increasing use of renewable energy sources including real-time energy monitoring systems, electric vehicles and their charging stations, solar panels and GSHP systems among other. (Lukkarinen et al. 2018; SYKE 2018)

Table 11. Greenhouse gas emissions of the municipality of Ii in 2007 and 2016 (SYKE 2018).

	Emissions in 2007 (kt CO_2-equivalent)	Emissions in 2016 (kt CO_2-equivalent)
Electricity	28,2	14,16
Transportation	45,76	45,21
Fossil fuels	14,37	13,34
Agriculture	8,99	10,31
Waste	3,9	3,1
Offset	-6,29	-40,28

One method to cut emissions in the municipality of Ii has been participating in the EURONET 50/50 MAX which is a programme supported by the European Union and aiming to decrease energy consumption in public buildings. At schools, the students develop methods to cut the energy consumption and the schools will be given half of the money they have saved in energy costs. Kuivaniemen koulu has been participating in the program since 2014 and they have been monitoring for example the indoor temperature and lighting. With the savings they have achieved, the school has purchased an outdoor table tennis table among other equipment used for sports and leisure.

7.2 Study site

The study focuses on a school, day-care centre and two terraced houses which are located close to one another. The school consists of two buildings, which are the main building and a building for technical work, but the main building has also a day-care centre which was built as an extension. The buildings are presented in figure 8 in their positions at the site. In this study, the (a) part of the building is referred as school, (b) part as day-care centre, and both (a) and (b) parts together as school building if not mentioned otherwise.

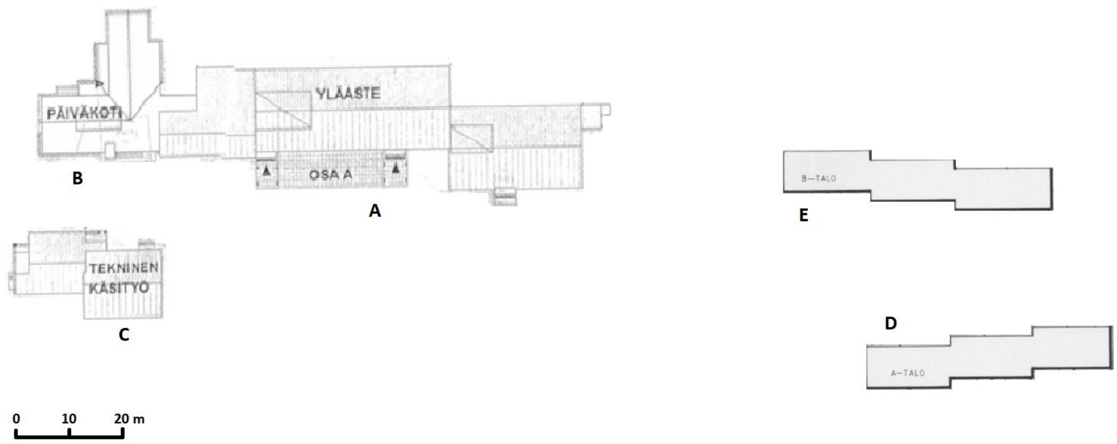

Figure 8. School (a), day-care centre (b), building for technical work (c), terraced house a (d) and terraced house b (e).

Table 12. Sizes of the buildings.

Building	Floor area (m^2)	Gross area (m^2)	Volume (m^3)
School (including building for technical work)	2951	3047	9740
Day-care centre	398,5	425	1550
Terraced houses	796	Unknown	Unknown

The school, presented in figure 9, was built in the mid-1950s and its external walls are double brick walls. In 2008, the building was completely renovated including the radiators but the building for technical work, presented in figure 10 and which was built in 1967, has not undergone any major renovations. The school has pupils in the grades from 1 to 9 and there are around 80 pupils in both grades 1 – 6 and 7 – 9. Thus, the total number of pupils is approximately 160 and the school personnel consists of around 20 people.

The first pupils start their school day at 9.00 in the morning and the school day ends at 15.00 the latest but the younger students leave the school already at 13.30 on average. Cleaners and personnel in the cafeteria start working already at 7.00 and the school has evening activities on Mondays, Tuesdays and Wednesdays at 17.00 – 20.00. On Tuesdays, the evening activity occurs in the building for technical work and other days in the main school building. The school is closed during weeks 10 and 43, the Christmas holiday and from the beginning of June until the early August totalling in around 13 weeks in a year. During this time the cafeteria is also closed.

Figure 9. Primary school.

Figure 10. Building for technical work.

The day-care centre, which is presented in figure 11, is in the main school building but it was built in 2008 as an extension. Unlike the main school building and the building for technical work, the day-care centre has underfloor heating. The day-care centre has approximately 20 children and it opens at 6.00 in the morning and closes at 17.00. Occasionally, the day-care centre is also open during weekends.

Figure 11. Day-care centre.

Next to the school, there are two terraced houses of which building (a) was built in the 1969 and building (b) in 1957. Both buildings are presented in figure 12 in which the building on the right is building (a), on the front is a warehouse and behind it building (b) can be seen. Apartments in each buildings are inhabited most of the time and there has been some renovation done such as triple glazing. In total, there are 12 apartments including five one-bedroom apartments and seven two bedroom apartments which have floor areas of 57 m^2 and 73 m^2 respectively.

Figure 12. Two terraced houses.

7.2.1 Consumption data of the study site

At the moment, the school uses district heating as its heating energy source and it has been used since early 1980s. Before district heating, peat and light fuel oil were used as heating sources. The school, day-care centre and two terraced houses have all their own connection to the district heating network resulting in three basic charges which must be paid. The thermal energy usages of the school and day-care centre have been recorded and the monthly usages are shown in table 13. As the monthly usages of the terraced houses were not known, they were estimated based on the total usage and are also presented in table 13. These values also include the heating energy which is used for DHW and the usage of water at the study site is presented in table 14.

Table 13. Heating energy demands of the school, day-care centre and terraced houses in 2017. *Monthly heating demands of terraced houses are estimates based on actual annual consumption and degree days.

Month	Heating energy demand of the school (MWh)	Heating energy demand of the day-care centre (MWh)	Heating energy demand of the terraced houses* (MWh)
January	93,76	9,22	42,43
February	95,74	8,9	40,24
March	88,47	7,98	37,93
April	66,36	6,63	31,3
May	55,75	5,82	22,61
June	22,98	2,52	4,44
July	11,47	1,43	0,85
August	17,7	2,01	2,92
September	33,74	3,49	13,49
October	67,65	6,45	26,62
November	77,63	7,19	32,03
December	93,32	7,45	38,17
Total	724,57	69,07	293,04

Table 14. Consumption of water at the study site in 2017.

Month	Water consumption of the school (m^3)	Water consumption of the day-care centre (m^3)
January	118	14
February	139	19
March	121	18
April	117	16
May	133	18
June	45	14
July	15	8
August	27	20
September	130	9
October	94	15
November	119	14
December	59	12
Total	1117	177

The total annual heating demand of these buildings has been 1086,68 MWh. However, it must be noted that the energy usage has had quite significant variation during the past years and for example the annual heating energy demand of the school has been 645 MWh in 2015 and 586 MWh in 2016. The day-care centre has slightly smaller energy demand per square metre which can be explained with day-care centre being a newer building and having underfloor heating. In a study conducted by Sarbu & Sebarchievici (2016), underfloor heating had few percentages higher COP than radiators and the radiators had 10 % higher energy consumption.

7.2.2 Ground properties at the study site

The ground properties at the site are presented in figure 13 and the possible location for the medium-depth borehole at the study site in figure 14. The soil is sandy till and its depth varies between 0 and 10 metres and therefore the bedrock is very close to the surface or even visible. The bedrock is migmatitic tonalite which means that it is a mixture of different rock types (GTK 2019). The properties of sandy till and tonalite are presented in table 15. The ground surface temperature at the site is 4,4 – 5,1 °C (Kukkonen 1986 & Pirinen et al. 2012) and the geothermal gradient is 0,8 – 1,2 °C/100 m (Martinkauppi 2019). By using these assumptions of the thermal properties of the ground, the assumed temperatures of the ground at different depths are presented in table 16. As it can be seen from the table, the temperature estimations at the depth of 2 km vary almost from 20,4 °C to 29,1 °C and the difference is as high as 8,7 °C.

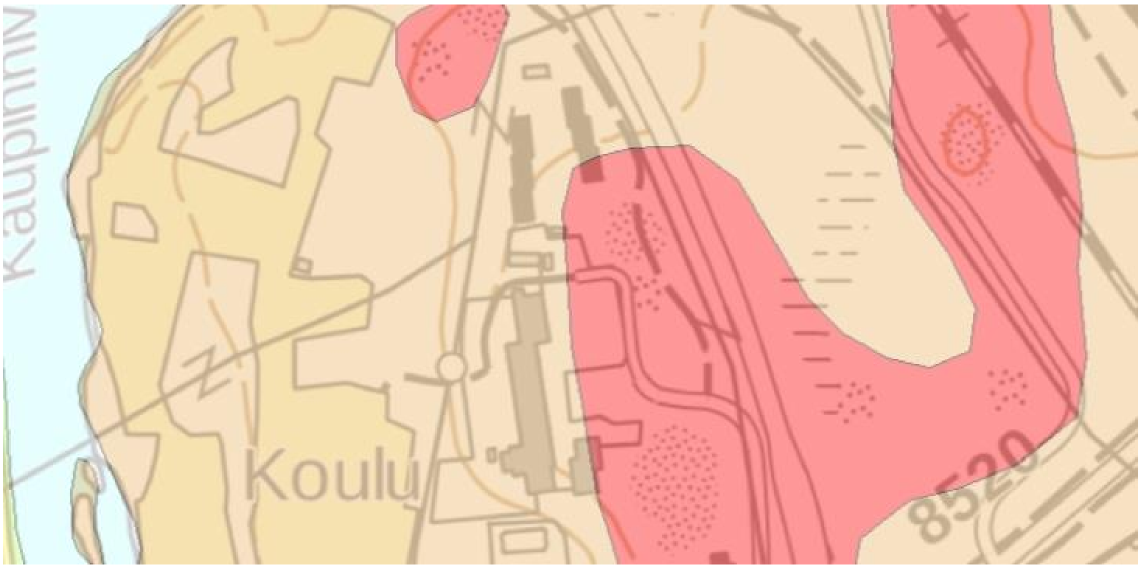

Figure 13. Ground properties of the site where brown presents till and red presents soil with a depth of maximum 1 m (GTK 2019).

Figure 14. Possible location for a borehole.

Table 15. Properties of tonalite and sandy till (Martinkauppi 2019).

	Tonalite	Sandy till		
		Minimum	Maximum	Average
Thermal conductivity (W/mK)	3,16	1	2,50	2
Volumetric heat capacity (MJ/m^{3}K)	2,4	1,51	2,45	2,1

Table 16. Estimated temperature of the ground at the site.

Depth (m)	Minimum temperature (°C)	Average temperature (°C)	Maximum temperature (°C)
0	4,4	4,8	5,1
300	6,8	7,8	8,7
1000	12,4	14,8	17,1
2000	20,4	24,8	29,1

According to GTK (2019), the ground at the site to the depth of 300 m stores 2,01 GWh of thermal energy and the constantly renewed thermal power is 4774 W. However, there is no standard of how much thermal energy a GSHP can provide at different parts of Finland due to complexity and variations at different sites. Based on experiments, it can be estimated that at the latitude of Ii a shallow GSHP system can provide annually 80 – 90 kWh/m and a medium-depth GSHP system approximately 250 – 300 kWh/m. Because the thermal conductivity of the ground at the site does not differ substantially from other rock types at the area (Peltoniemi & Kukkonen 1995; GTK 2019; Arola 2020), 85 kWh/m for shallow GSHP system and 275 kWh/m for medium-depth GSHP system are decided as the values for the calculations in this study.

8 RESULTS

Two different types of GSHP systems and a possibility to use DSM at the school building are investigated in this study. To replace the district heating system in Kuivaniemen koulu, GSHP systems with two different depths of the borehole are considered and the comparison is done between a medium-depth borehole with a depth of 2000 m and conventional boreholes with a depth of 300 m. In addition, the possibility of demand-side management will be investigated in order to cut the costs and make the investment of the new energy system profitable.

8.1 Replacement of district heating

In this study both conventional and medium-depth boreholes are considered to replace the old heating method. Outlines of sizing a GSHP system were discussed in section 3.3 and regulations regarding to them in section 6.1. The main issues to consider in the sizing procedure are the expected amount of energy the different sized GSHP systems can produce at the site, available land for the boreholes, and the energy need of the study site. In addition, it must be decided whether the whole energy need is covered with GSHP systems or if additional heat source is required.

8.1.1 Heating energy need

As mentioned, one of the main decisions during sizing procedure is to choose if the energy system will cover either full heating energy demand or only part of it. Because shallow boreholes are common, the energy production of a shallow borehole is relatively easy to estimate and therefore full coverage is easy to design and prosecute. However, it is safer to not cover full heating energy demand with the medium-depth GSHP system due to the lack of research and experience on such system in Finnish conditions. On the other hand, the main point of this study was to replace district heating fully as it might not be usable in the future. Nevertheless, the options are to use GSHP system to cover the full energy demand or to invest in an additional energy source. In this study, the new heating system is decided to not cover the full energy demand. However, as described in section 3.3, energy coverage of over 95 % can be often achieved even if the system is sized to cover approximately 70 % of the peak power demand.

Table 13 presents the heating demand of the buildings at the study site in 2017 which was 1086 MWh in total. This value cannot be, however, used as the amount of energy which needs to be fulfilled without taking a closer look to the weather during that year because the energy demand varies depending on the outdoor temperature. In figure 15, degree days in Oulu in 1995 – 2019 are presented. The values vary between 4119 and 5605 meaning that the heating demand vary quite significantly depending on the year. In 2017, the value was 4821 being only slightly off from the average of 4844 which was calculated using years 1995 – 2019.

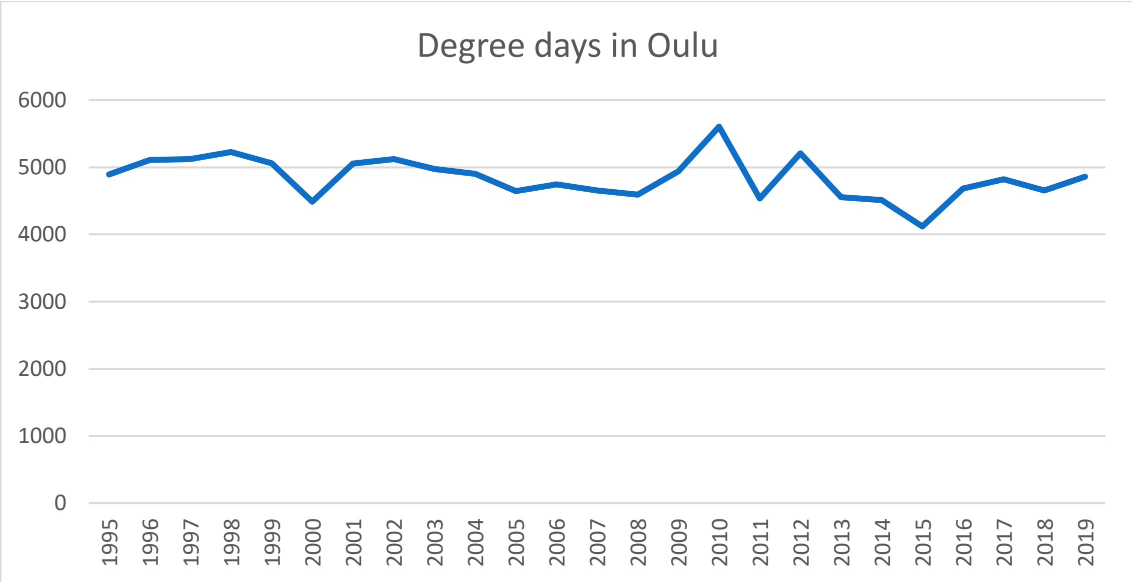

Figure 15. Degree days in Oulu from 1995 until 2019.

Heating energy consumption of 2017, which is presented in table 13, includes heating energy used for DHW and since its amount is not depending on the weather, it should be subtracted from the total energy consumption. The heating energy needed for DHW is calculated with the use of equation (4) presented below. The consumed water in cubic metres at the school and day-care centre are presented in table 14 and because the proportion of DHW is not separated, it is assumed that 30 % of the total water consumption is DHW. (Motiva 2019a) Consequently, the DHW heating energy consumption of the school and the day-care centre are calculated to be 19 435,8 kWh and 3079,8 kWh totalling in approximately 22,5 MWh. Figures 16 and 17 present the proportion of heating energy which are used for space heating and DHW.

$$Q_{DHW} = 58V_{DHW} \tag{4}$$

In which, Q_{DHW} is heating energy consumption of domestic hot water (kWh)

V_{DHW} is volume of domestic hot water (m^3)

58 is the required energy to heat the water when temperature change of the water is 50 °C (kWh/m^3)

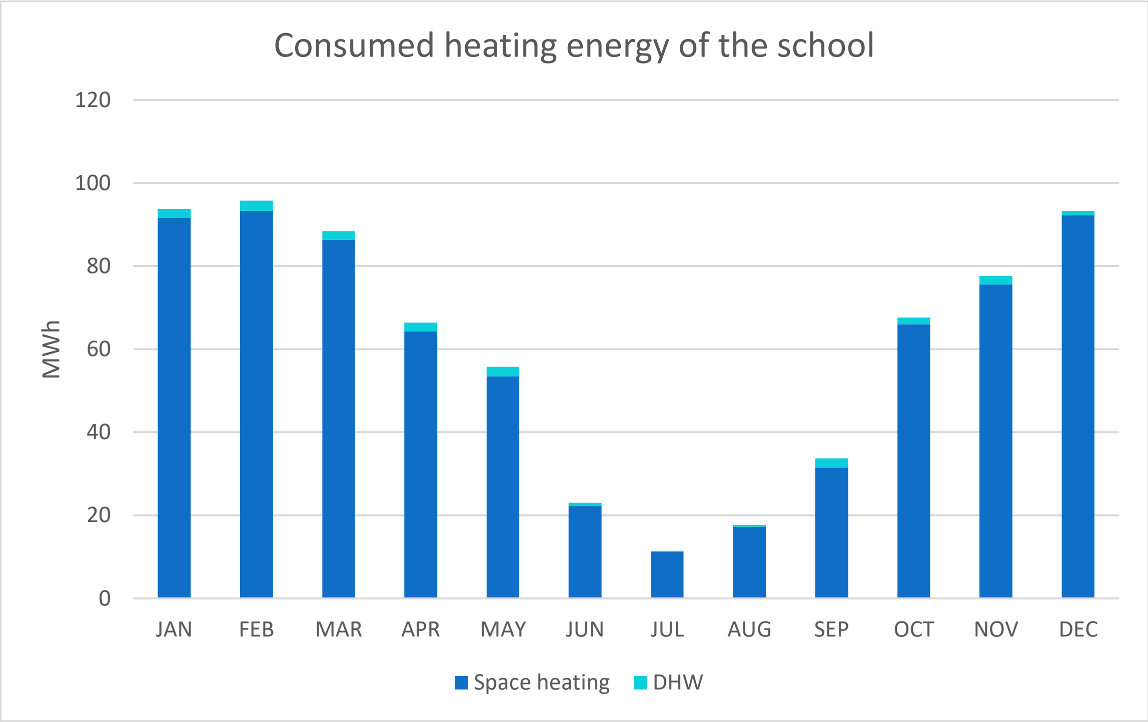

Figure 16. Consumed heating energy of the school in 2017.

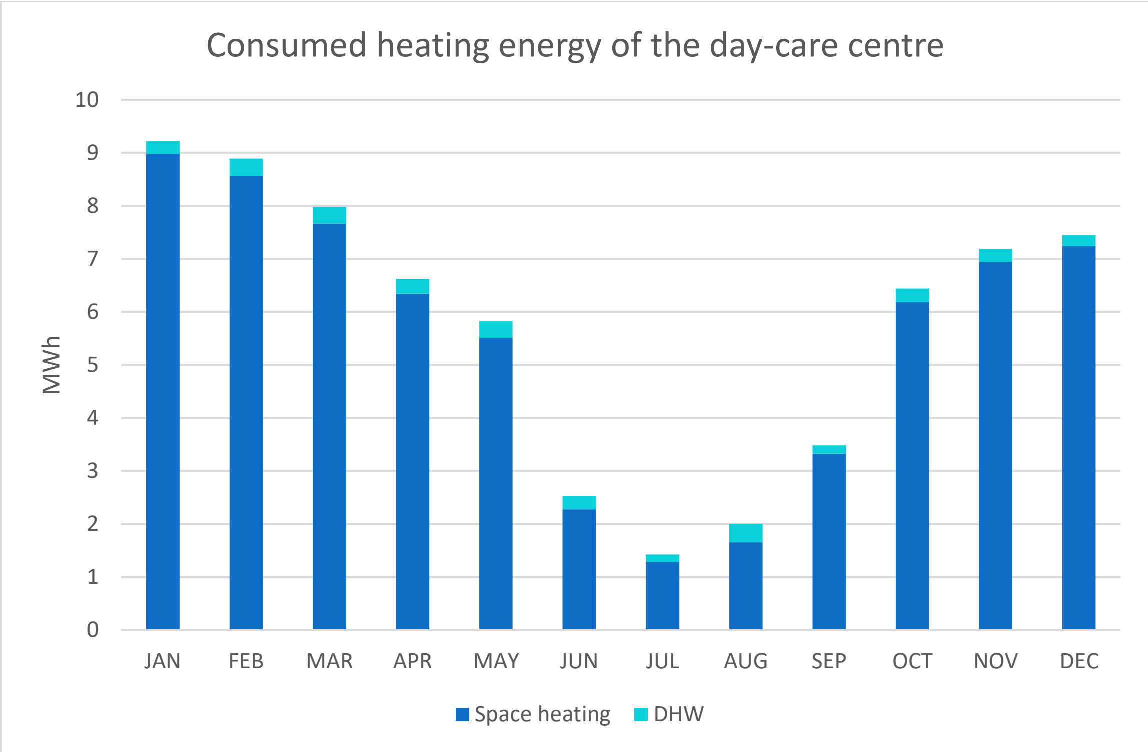

Figure 17. Consumed heating energy of the day-care centre in 2017.

There is no data available about the water usage of the terraced houses and therefore the energy demand of DHW is estimated based on the floor area and the results are presented in figure 18. According to Motiva (2019a), the energy usage can be calculated with the assumptions that in residential buildings DHW consumption is 0,6 m^3 for each square metre of gross area. With the assumption that the gross area of the terraced houses is 800 m^2, annual DHW usage is 480 m^2. Because DHW consumption does not have similar seasonal variation as in the school and day-care centre, the monthly usage is estimated to be 40 m^2 each month. With the use of equation (4), the annual energy need of DHW is calculated to be 27,84 MWh and monthly 2,32 MWh.

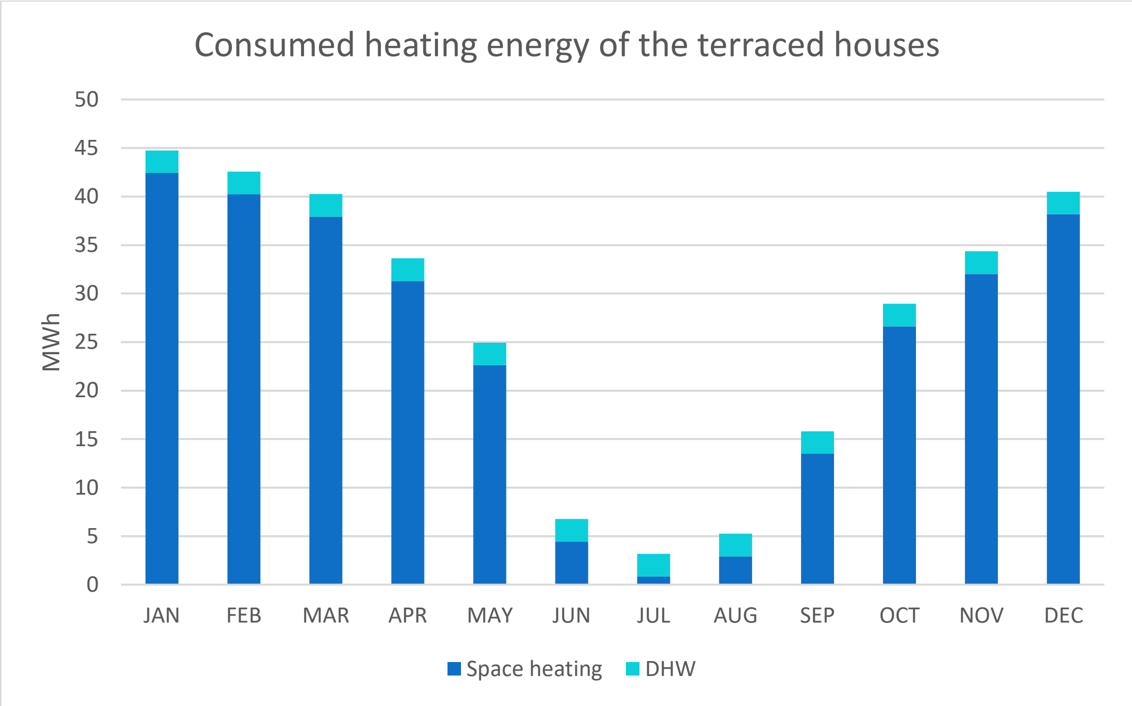

Figure 18. Consumed heating energy of the terraced houses in 2017.

The average heating energy needs of the buildings at the study site are presented in table 17 and these values are used while sizing the heating system. When considering the last 25 years, as seen from figure 15, 2010 was the coldest year having 5605 degree days. The school, day-care centre and terraced houses would have required 1256 MWh of heating energy in total which is significantly more than the average energy need of 1093 MWh.

Table 17. Average annual heating energy needs of the buildings.

Building	Space heating (MWh)	DHW (MWh)	Total (MWh)
School	709,5	19,44	728,94
Day-care centre	66,3	3,08	69,38
Terraced houses	266,46	27,84	294,3
All	1042,26	50,36	1092,62

8.1.2 Energy production of the boreholes

As mentioned in section 7.2.2, the annual gained energy at the study site is estimated to be approximately 85 kWh/m if the borehole is 300 m deep and 275 kWh/m for a borehole with a depth of 2000 m. These values are estimations made by the personnel of the Geological Survey of Finland and they are used in the following calculations. The value of the shallow borehole is reliable and based on extensive experimental data. On the contrary, the value for medium-depth borehole is a rough estimate and therefore it should be noticed that the actual heating potential of the borehole could vary significantly.

The mentioned values of energy production at the site per metre only include the energy which can be gathered from the ground. Therefore, the COP values are required to discover the energy which can be used for heating. For shallow boreholes, Juvonen & Lapinlampi (2013) estimates the COP to be 3 and according to Juuti (2020) the only operating medium-depth borehole in Finland should have a COP of 3,5 – 4,5 and 3,5 is chosen to be the used value in this study. With these values, it can be estimated that a 300 m deep borehole produces annually 38,25 MWh and 2000 m deep borehole 770 MWh. If there would be seven boreholes with a depth of 300 m and totalling in 2100 m, their annual production would only be approximately 270 MWh being significantly smaller than what could be produced with a medium-depth borehole.

The estimation of the energy production which a medium-depth borehole can provide at the study site is clearly smaller than the annual production of the only operating medium-depth GSHP system which is over 1000 MWh as stated in section 2.3.1. Even though the climate has an effect on the ground temperature, it does not play as significant role in the heating potential of medium-depth boreholes than conventional ones. The reason for this is that deep in the ground only a small portion of the heat is originated from the sun and thus has little to do with the outdoor temperature. Therefore, if the energy production is compared to the annual production of the medium-depth GSHP system in southern Finland, other factors than climate should also be considered as causes for a difference in energy production. In this case, the most probable reasons are the ground characteristics and charging of the borehole during summer which increases the temperature in the ground and results in higher yield. However, in this study, charging of boreholes is not considered due to the lack of cooling needs at the properties.

8.1.3 Required boreholes

As stated in section 8.1.1, the average annual heating energy consumption of all buildings is 1093 MWh. Since one medium-depth GSHP system is estimated to provide annually 770 MWh, one borehole cannot provide enough energy. However, the school and the day-care centre have a consumption of 798 MWh and therefore one medium-depth borehole could be sufficient for the school and the day-care centre. In that case, the terraced houses should invest in an additional heating system when district heating can be no longer in use. If all buildings would use shallow boreholes which have an annual production capacity of 38,25 MWh, 29 boreholes should be constructed to cover the full energy demand. To cover the energy demand of terraced houses with shallow boreholes, 8 boreholes would be required.

In figures 19 and 20, possible locations for boreholes are shown. The location for a medium-depth borehole is the same which is presented in section 7.2.2 in figure 14. The location was suggested by an employee of the municipality of Ii mainly because it is close to the mechanical room of the school building. This suggested location is considered because it is also suitable due to being far enough from the roads and property boundaries. As stated in section 6.1, the borehole may must be located 7,5 m from the boundary of neighbouring property, 15 m from another borehole and 20 – 50 m from roads. In addition, they may not be nearer than 3 – 5 m from pipes. As the location of pipes is not known, they are not considered in this study.

The locations of the shallow boreholes are harder to plan than the location for a medium-depth borehole due to their vast number. A big part of the property is covered with playground or trees of which neither is an ideal place for a borehole. In addition, buildings, car park and roads must be avoided. Since there is only little free space left, playgrounds cannot be avoided when choosing the locations of the boreholes. Even though according to the regulations the boreholes should not be closer than 15 m away from one another, the distance should preferably be longer in order to avoid taking too much heat from the ground during a short time period. Figure 20 does not present the exact locations which are proposed for the boreholes but rather demonstrates the area which is required.

Figure 19. Map of the study site with red lines presenting plot borders and red dot presenting a possible location for a medium-depth borehole (Maanmittauslaitos 2020).

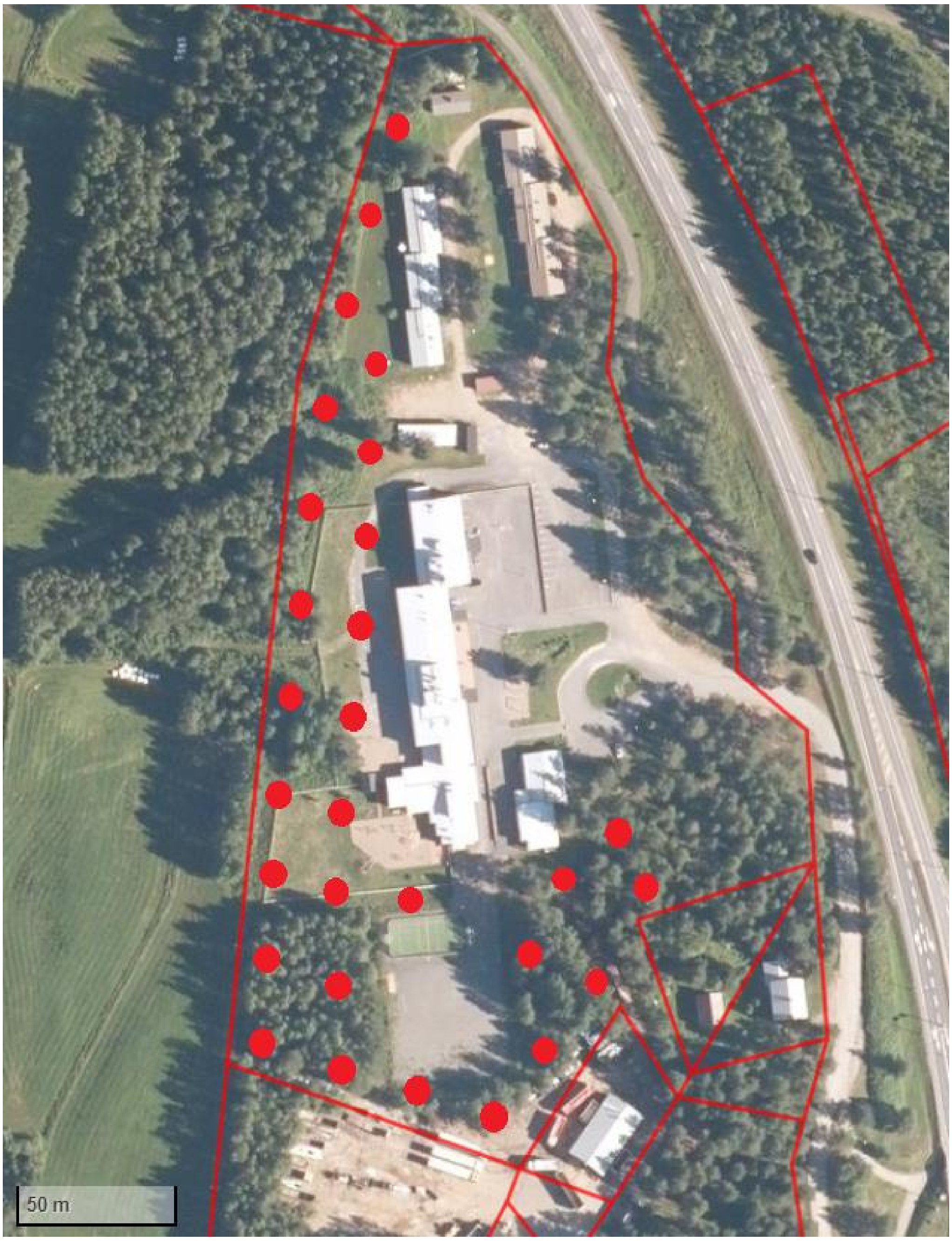

Figure 20. Map of the study site with red lines presenting plot borders and red dots presenting possible locations for shallow boreholes (Maanmittauslaitos 2020).

Three quotations were requested from Finnish companies for the study site in order to obtain an idea of the costs of a conventional GSHP system and one was received from Gebwell. The quotation was requested for school and day-care centre, and for the terraced houses separately resulting in two separate systems and prices. In the quotation, it was suggested to construct 9 boreholes with a depth of 306 m for the school and day-care centre and 9 boreholes with the depth of 285 m for the terraced houses. These boreholes have a total depth of 9603 m while the suggested total depth of this study is 8700 m meaning that the suggestion of Gebwell is to construct 3 boreholes more. The biggest difference between the estimation made in this study and the suggestion made by Gebwell is the COP. While the used value in this study was 3, Gebwell used values 4 and 3,67. Nevertheless, the estimation of the gained energy per metre was very close and the difference was only 2 kWh/m. (Liukkonen 2020)

8.2 Demand-side management

A building itself can be used as a thermal storage and the ability of storing thermal energy depends on the building material. The proposed strategy to use demand-side management in this study is to use building's thermal mass to store heat by preheating it during the off-peak periods. Only the educational buildings are considered to be used in demand side management because there is no occupation during the off-peak periods unlike in the terraced houses. The school has a façade made of bricks and thus it is categorized as a heavy which means the building has a high capacity of storing heat. On the contrary, buildings with lower thermal masses, such as buildings made of wood or steel, are categorized as light. (Kensby et al. 2015)

This strategy to control the timing of electricity usage is considered because the electricity is cheaper at nights with electricity contracts which use spot prices. The heating system can be shut down during the on peak periods and before people leave the building. There are few possibilities of executing this strategy: one being short preheating period before people arrive the building and another longer preheating period which would decrease even more the need for heating during the most expensive hours in the morning. In this study, we concentrate on longer heating period due to the building properties.

8.2.1 Thermal properties of the building

To estimate the thermal conduction of the school building, equation (3) presented in section 5.1 can be used. The estimation is done with the use of values from table 13 and outdoor temperatures in 2017. The closest observation station to Kuivaniemen koulu is at Kemi-Tornio airport located 40 km northwest from the study site and its data is used in the calculation. The temperature measurements of 2017 are presented in figure 21 where the assumed indoor temperature of the school is also presented.

As stated in table 9, which presents values used in E-value calculation, the heating and cooling limits for educational buildings are 21 °C and 25 °C respectively. It can be assumed that the indoor temperature has been between those values in Kuivaniemen koulu in 2017. Because they were participating in the EURONET 50/50 MAX programme during the studied year, it is estimated that the temperature has been quite low to achieve reductions in the energy bill and therefore the indoor temperature is set to be 21 °C in the following calculations.

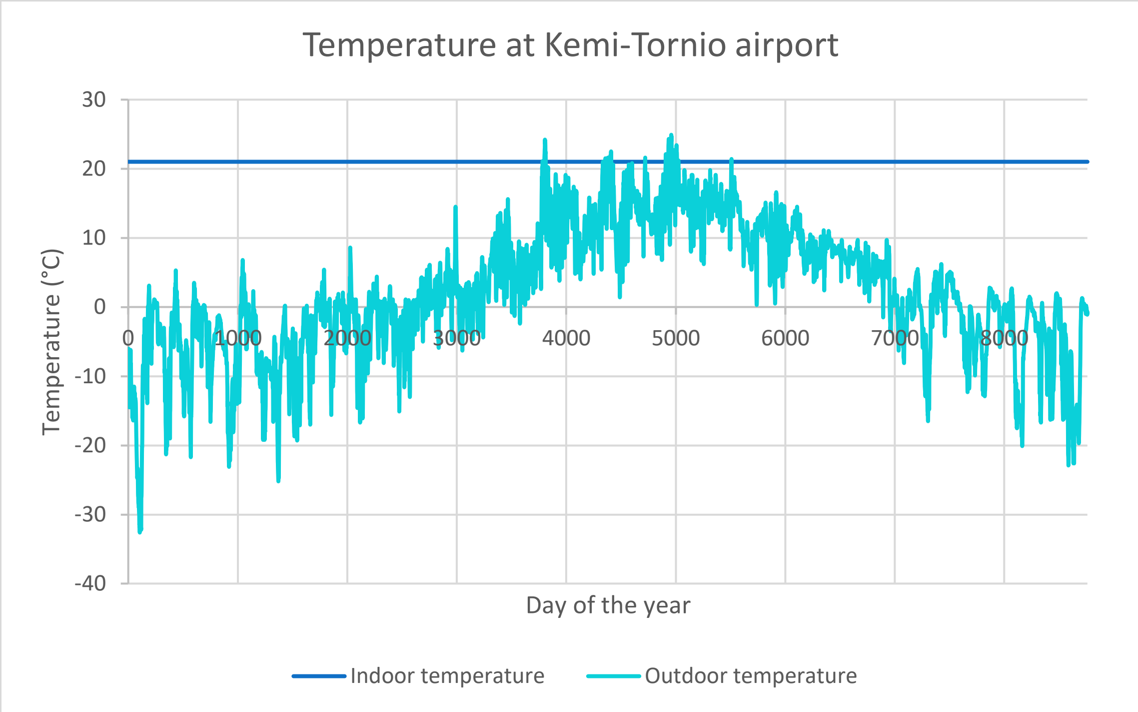

Figure 21. Outdoor temperature at Kemi-Tornio airport during 2017.

Because the thermal energy consumption data of Kuivaniemen koulu includes energy used for DHW, the heating energy of DHW must be subtracted from the total energy consumption in order to calculate the heat losses in the building. The subtraction was done in section 8.1.1. and since the space heating energy consumption is known, heat losses in the school building are determined next. By using equation (5) it is possible to estimate total heat losses including losses through conductance, ventilation and air-leakages (The National Building Code of Finland D5, 2013) and the initial values and results are presented in table 18. As discussed in section 5.1, buildings have both heat losses and heat gains and it should be noticed that the calculated heat losses in table 18 also take into account heat gains caused by for example people and electrical devices because the net energy consumption is used in the calculations.

$$H = \frac{Q}{(T_i - T_o)\Delta t} 1000 \quad (5)$$

In which, H is heat loss (W/K)

Q is space heating energy consumption (kWh)

T_i is temperature indoors (°C)

T_o is temperature outdoors (°C)

Δt is time (h)

1000 is required to get the result in watts

Table 18. Degree-hours, space heating energy consumption and heat losses of the study site.

Month	Degree-hours in 2017	Heating energy used for space heating of the school (MWh)	Heating energy used for space heating of the day-care centre (MWh)	Heat loss of the school (W/K)	Heat loss of the day-care centre (W/K)
January	21239,9	91,71	8,98	4317,67	422,67
February	19303,8	93,32	8,56	4834,35	443,4
March	18809,5	86,36	7,67	4591,54	407,76
April	15972,2	64,32	6,35	4027,26	397,35
May	12592,7	53,44	5,51	4243,39	437,62
June	6773,2	22,2	2,28	3277,18	336,68
July	4520,1	11,21	1,29	2479,81	285,35
August	5764,5	17,23	1,66	2989,02	287,8
September	8804,45	31,48	3,33	3575,24	378,04
October	13694,7	66,01	6,18	4820,43	451,56
November	16266	75,56	6,95	4645,24	426,99
December	20619,5	92,29	7,24	4476,03	351,13

Heat loss of the school and day-care centre vary depending on the month. Explanation for this can be for example the ventilation which can be reduced when the school is closed. In addition, the initial values of consumed energy are not precise because the documentation is not automated and most possibly no one has been marking down the values during the weekends. Therefore, if the first day of the month has been for example on Sunday, the value has been marked down either on Friday or Monday and there would be approximately 1,5 days too little or too much of consumption recorded. In this case, the consumption of one month would be about 5 % too high or low.

In table 5, the internal heat gains of different types of buildings are presented. In educational buildings, the internal gains are 36 W/m^2 which are produced by people, appliances and lighting. Thus, it can be determined that the internal heat gains are approximately 72 000 W at the study site during the use of the school and day-care centre. When also occupancy rate and period presented in table 5 and internal gains considered, the average heat loss at the school and day-care centre is determined to be approximately 5660 W/K. By using this value and using a sizing outdoor temperature of -32 °C (Finnish Meteorological Institute 2020) meaning that the maximum temperature difference between indoors and outdoors is 53 °C, the peak power demand of the school and day-care centre can be determined to be 300 kW.

8.2.2 Electricity prices

The final price of the electricity consists of electricity sales, distribution rate and taxes. In Finland, consumer can decide the company from which they purchase their electricity but they must pay their distribution costs to the company which operates the network at their area. There are several different electricity sale contracts to choose from which have varying pricing methods and electricity production types allowing consumers to cut their emissions by choosing renewable energy. The price of electricity can be fixed or based on for example season or time of the day. Some companies offer different price for electricity during daytime and nighttime while the price in other contracts can be based on the real-time spot price and therefore it changes usually every hour of the day.

In this case study, the electricity contract based on spot prices is considered to be used in order to benefit from demand-side management. Figure 22 presents the average spot prices in Finland in 2017 – 2019 and it can be clearly seen that the cheapest electricity is during nighttime and the most expensive in the morning at 7.00 – 11.00. On average, electricity costs approximately 34,09 €/MWh between 00.00 and 07.00 and 48,72 €/MWh between 7.00 and 11.00 being 41 % more expensive than electricity during the night and having a price difference of 14,63 €/MWh.

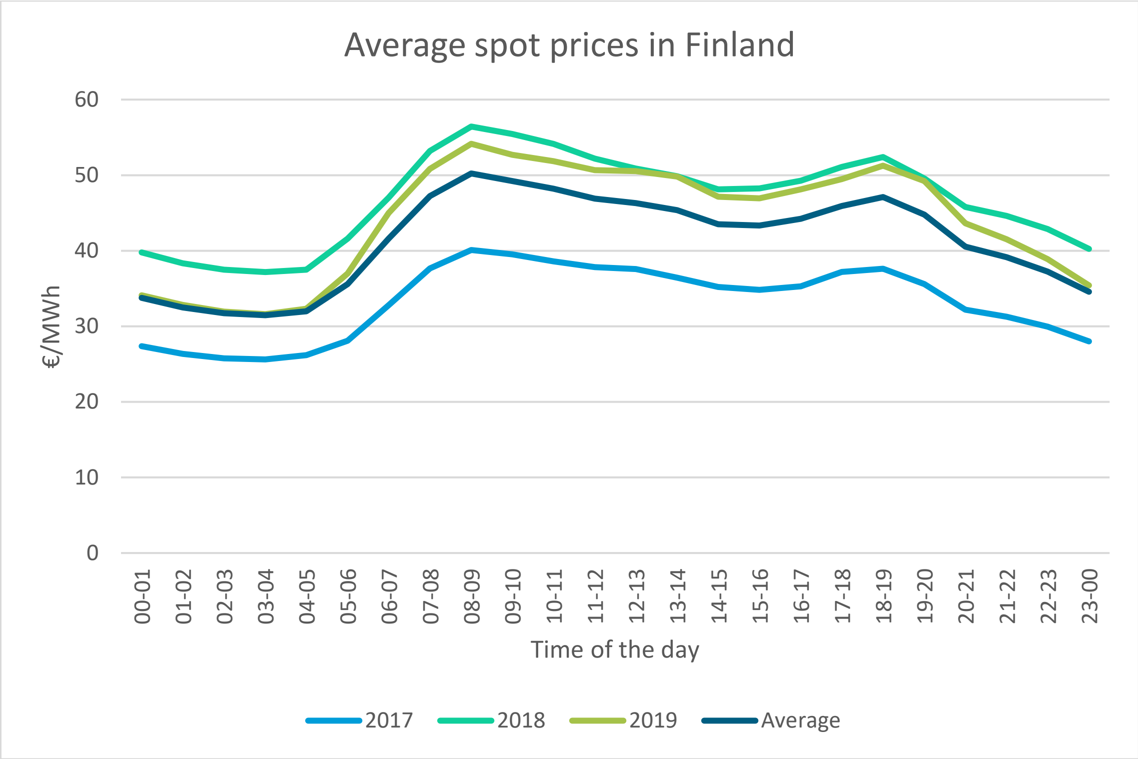

Figure 22. Average spot prices in Finland at different times of the day.

The spot prices vary, however, depending on the season. As seen in figure 23, the biggest difference in spot price in 2017 – 2019 when comparing the average price at 00.00 – 07.00 and 07.00 – 11.00 is during the winter months when the heating demand is the highest. If the seasonal difference and the heating demand of Kuivaniemen koulu is taking into consideration, the price difference of electricity at night and in the morning will decrease from 14,63 €/MWh to 13,32 €/MWh. This calculated value of 13,32 €/MWh can be used to determine the savings which can be achieved if the time of the heating is shifted to the nighttime instead of the morning.

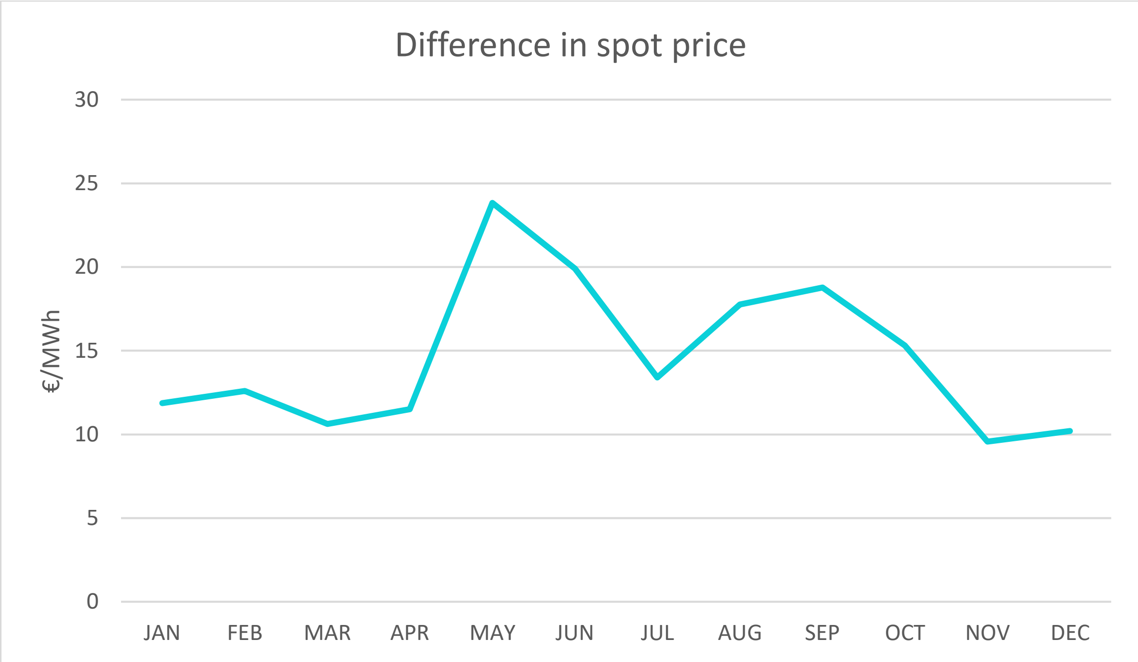

Figure 23. Average spot price difference at night and in the morning during different months in 2017 – 2019.

In Kuivaniemi, where the study site is located, the electricity network is operated by Rantakaira. They offer few different contraction types for distribution including pricing being fixed, based on the highest power output of the day and varying depending on the season or time of the day. A contract based on the time of the day could be beneficial at the study site if DSM is used. In this contract type, there is a lower fee at 22 – 7 and higher fee at 7 – 22. The nighttime distribution fee is 1,10 c/kWh without taxes and 4,16 c/kWh including taxes, and the daytime fees are 2,10 c/kWh and 5,40 c/kWh respectively. In addition, there is a base distribution fee which is be determined by the fuse size. (Rantakaira 2020a; Rantakaira 2020b) However, as the study site has a high energy demand, it might be that they are not allowed to sign a contract where the costs depend on the time of the day.

8.2.3 Potential of demand-side management

In this study, it is investigated if the heat required during the first hours when the school building is in use could be generated at night when the electricity prices are lower. As seen from figure 22, the electricity price starts to become more expensive already at 7 in the morning which is also the time when some personnel of the school start working. It is decided that the study concentrates on preheating at night to avoid heating during the first four hours of the morning which means that there would be no heating between 7 and 11. It should be noted, however, that even though it is assumed that the school does not require any heating at 7 – 11, in reality some of the heat generated at night would be lost before the morning. Therefore, the additional heat generated at night should be higher than the amount which is calculated to be the energy demand in the morning.

Since the peak power demand of the school and day-care centre was determined to be 300 kW and the GSHP system is sized to cover approximately 70 % of the peak power demand (Motiva 2019b), the peak power of the GSHP is determined to be 210 kW. The sizing outdoor temperature is -32 °C (Finnish Meteorological Institute 2020) which means that with heat loss being around 5660 W/K on average when there are no internal heat gains, the school and day-care centre can be heated fully with the GSHP system when the temperature stays above -16 °C. However, it should be noted that since the average heat loss value of the coldest months was used during the determination of the peak power, the peak power of the GSHP should possibly be higher. In addition, the DHW requires heat and therefore increases the peak power demand of the GSHP system but it is not considered while determining the feasibility of DSM.

If it is assumed that the temperature stays constant during the night and the morning, the preheating period is five hours and the hourly internal heat gains are on average approximately 36 kWh, with a temperature of -2 °C or above the GSHP system is able to generate as much additional energy at 2.00 – 7.00 as the study site requires at 7.00 – 11.00. When temperature stays at -2 °C, the study site requires 376 kWh at 7.00 – 11.00 meaning an hourly average of 94 kWh. At night without any internal heat gains, the hourly heating energy demand is 130 kWh and thus the heating system is able to generate hourly 80 kWh of additional energy. If the preheating period was to be extended to seven hours, the minimum temperature would be lowered from -2 °C to -5 °C. In this assumption, the internal heat gains are expected to be 36 kWh, which is half of the determined internal heat gains of the time when the school building is in use, because at 7.00 – 9.00 the pupils of the school have not arrived to the building yet.

During the reference year 2017 which has been used in this study, there were 128 days when the average temperature was below -2 °C at 2 – 7 and 80 days when average temperature was below -5 °C at 0 – 7 during the night. This means that there is a significant amount of days when the energy required to heat the first four hours when the school is in use cannot be generated during the night. However, there were only 14 days when the temperature at night was below -16 °C meaning that the GSHP system cannot generate enough energy even for the time being and an additional energy source must be used. Thus, the number of days when at least some load shifting could be done is high.

If it is assumed that the GSHP system would operate with its peak power every night during the preheating period if that is required to cover the heating demand of the night and the first four hours of the morning, with a preheating period of five hours the GSHP system would generate annually 92 MWh of additional energy and 104 MWh if the preheating period is extended to seven hours. As the price difference of electricity at night and in the morning was determined to be 13,32 €/MWh in section 8.2.2, the annual savings with a preheating period of five hours would be 410 € if the COP is 3 as expected for shallow boreholes and 350 € if the cop was 3,5 as expected for medium-depth borehole. With a preheating period of seven hours, the annual savings are 460 € and 400 € respectively. Even though these savings are calculated based on only one year, the result shows the scale where the annual savings could be at.

8.3 Costs

Costs of a GSHP system consist of several factors such as price of the heat pump and other equipment, performance of the system, drilling, electricity costs and maintenance (Mazzotti et al. 2018). Tom Allen Senera (2019) and Lämpöykkönen (2019), which are both Finnish companies providing shallow GSHP systems, and Kontu et al. (2015) all estimate a single borehole GSHP system to have investment costs around 15 000 – 20 000 €. Tom Allen Senera (2019) estimates that a GSHP system for a commercial building with a heated area of 1000 m^2 costs approximately 100 000 €, for an area of 2000 m^2 costs 160 000 – 180 000 € and for an area of 10 000 m^2 costs 700 000 €. Annual maintenance costs of a GSHP are 1 % of the investment according to Paiho et al. (2017) and 0,6 % according to Niemelä et al. (2017).

Because shallow GSHPs are relatively common, their prices are rather easy to estimate. However, because deeper boreholes are rarely constructed, their costs are harder to predict. Both shallow and medium-depth GSHP systems use similar equipment except the medium-depth GSHP uses coaxial heat exchanger instead of single U-pipe heat exchanger, which are both described in section 3.1.1, and therefore the equipment does not cause significant additional costs to medium-depth GSHP systems. The biggest difference in the costs is caused by drilling and especially with deeper boreholes the costs of the drilling might become the most expensive part of the investment (Mazzotti et al. 2018) and therefore their costs are important to determine during the cost analysis (Gehlin et al. 2016).

The challenge in the estimation of drilling costs is caused by the non-linear function of the costs per metre. While drilling, the first metres which are required to be cased can be up to 5 times more expensive than the un-cased metres. In addition, the deeper the drilling occurs the more risks, such as clogging, there are, and time-consuming recovering of the drill might be required. (Gehlin et al. 2016) Mazzotti et al. (2018) have estimated drilling costs in Sweden by conducting a survey which was done during a Swedish driller association gathering. Based on the survey, the drilling costs for a metre are 13 – 22 € for a borehole with a depth of 300 m and 17 – 36 € if the borehole has a depth of 600 m.

In Finland, there are only few deeper boreholes constructed and therefore the prices are challenging to estimate. The first deeper boreholes are also significantly more expensive than same kind of boreholes in the future when more than 10 boreholes have been constructed. However, it can be estimated that the investment cost of a medium-depth borehole including all the equipment and work would be 30 % higher than if the same amount of energy would be gathered with conventional boreholes. In the future, it is possible that the costs will be near the same or even lower than the costs of shallow boreholes. (Niemi 2020)

As explained in section 8.1.3, a quotation was received from Gebwell concerning GSHP systems. For the school and day-care centre, the cost would be 330 000 € and 130 000 € for the terraced houses but the cost estimations do not include installation costs (Liukkonen 2020). As mentioned, the medium-depth GSHP system is estimated to be 30 % more expensive than conventional system and since it could only cover the heating demand of the school and day-care centre, its costs are estimated to be 429 000 €.

According to the quotation, annual heating costs of a conventional system for the school and day-care centre would be 25 113 € and costs for the terraced houses 10 118 € including the use of the heat pump and additional electricity costs caused by cold weather when the GSHP system is not able to cover the heating demand (Liukkonen 2020). If the operation costs are calculated according to the sizing made in section 8.1.3, the operation costs would be slightly higher due to the smaller COP. On the other hand, since COP should be higher with deeper boreholes, the operation costs of the heat pump using a medium-depth borehole as a heat source should not be as high as they are with shallow boreholes. However, as the heat gain of the medium-depth GSHP system is very uncertain, the operation costs are hard to estimate.

At the moment, the buildings at the study site use district heating which costs 62 €/MWh. In addition, the school, day-care centre and the terraced houses have each individual basic fees which are 3932,28 €, 539,16 € and 1412,04 € totalling in annual costs of 5883,48 €. In order to calculate the total annual heating costs, the average energy consumption of 1092,62 MWh is used. With average consumption, the energy fee is 67 742,44 € and thus the total costs are 73 625,92 €. The savings made with a conventional GSHP system are presented in table 19 and savings made with a medium-depth GSHP system in table 20.

Table 19. Heating costs of a conventional GSHP system.

Building	Current annual costs	Annual operation costs of a conventional GSHP system	Annual savings
School and day-care centre	53 967,28 €	25 113 €	28 854,28 €
Terraced houses	19 658,64 €	10 118 €	9 540,64 €
Total	73 625,92 €	35 231 €	38 394,92 €

Table 20. Heating costs of a medium-depth GSHP system.

Building	Current annual costs	Annual operation costs of a medium-depth GSHP system	Annual savings
School and day-care centre	53 967,28 €	21 525,43 €	32 441,85 €

The payback time of the investment is calculated by dividing the investment cost with annual savings. If all buildings would use shallow boreholes as their heat source, the payback time would be 12 years. If medium-depth borehole would be constructed to cover the heating demand of the school and day-care centre and the annual savings are expected to be a little higher due to a higher COP, the payback time would be 13 years. As the lifetime of a compressor is 15 – 20 years according to Motiva (2019b), during the lifetime of both GSHP systems the costs should be less than if the current heating system is not replaced. Therefore, both conventional and medium-depth systems seem to be viable options but the uncertainty of real costs and production rate of a medium-depth system should be considered. In addition, the savings are based on the quotation from Gebwell and they are the maximum savings which could be achieved since the COP in the quotation is determined to be clearly higher than what it is assumed to be in this study.

9 DISCUSSION AND CONCLUSIONS

This thesis was done to study medium-depth GSHP systems and their use in Finland which is still at a very early stage. Geothermal energy in general is, however, a relatively common energy source in Finland but the usage is concentrated on using shallow boreholes with a depth of 120 – 300 m. Other methods to utilise geothermal energy include deeper boreholes, collecting heat near the ground with hundreds of metres long ground loop, and utilising surface waters or groundwater. The system can be closed or open meaning that there is either a closed pipe system where a fluid circulates and collects heat from a medium or an open system where the circulating fluid can be part of the body of water which is used as a heat source.

Due to the newness of utilisation of 1 – 7 km deep boreholes in Finland, their naming has not yet settled. In this study, these deeper boreholes are further divided into 300 – 2000 m deep medium-depth boreholes (*keskisyvä maalämpö*) and deep boreholes (*syvä maalämpö*) which are deeper than 2 km. The construction of first medium-depth borehole and deep borehole in Finland have started during the past few years but there are already plans to construct more. At the moment, the regulation of shallow boreholes with a depth of few hundred metres is basically the same as of deeper boreholes which can reach a depth of several kilometres. Medium-depth and deep boreholes are not included in several acts and they do not require environmental impact assessment, and therefore the regulation of medium-depth and deep boreholes seem to be insufficient.

The municipality of Ii is a forerunner in renewable energy technologies and therefore Iin Micropolis, which is a development company located in Ii, was interested in the possibility of using medium-depth GSHP system at some of their properties in the municipality. Heating systems using both conventional 300 m boreholes and 2 km deep medium-depth borehole were sized for the study site which was a school, day-care centre, and two terraced houses located in a near proximity from the educational buildings. It was calculated that one 2 km deep medium-depth borehole could produce annually 770 MWh and thus only provide energy for the school and day-care centre meaning that the terraced houses would need a separate heating system. If conventional 300 m deep boreholes were used to cover the energy demand of all buildings at the study site, there would be a need to construct 29 boreholes which produce annually 38,25 MWh each.

The payback times of both systems were evaluated and for shallow boreholes it was determined to be 12 years and 13 years for medium-depth borehole. When considering these results, it seems like the difference in payback time is rather small between shallow and medium-depth boreholes. In addition, since the lifetime of a compressor is approximately 15 – 20 years, both GSHP systems seem feasible even though the payback times are calculated with an optimistic estimation of COP. However, the fact that the first medium-depth GSHP system in Finland started operating only few months ago causes a significant uncertainty on evaluation of both production rate and investment costs of such system since there is only little information available. The values used in the calculations were mostly estimates made by the specialists from the Geological Survey of Finland and Qheat which was the company to construct the first medium-depth GSHP system in Finland. In addition, the costs of medium-depth GSHP systems could become rapidly cheaper if their popularity increases and drilling methods develop to have higher performance.

At the study site of this study, a medium-depth borehole is a feasible option but if one was decided to be constructed, the constructor must take into consideration the uncertainties caused by a novel technology. The calculated payback time is only a little higher than in a conventional system but only if there does not appear any significant obstacles during construction. One of the biggest advantages would be to avoid having tens of boreholes which could prevent cutting trees from the property and would enhance the safety of the children. This study has not, however, taken into consideration the possible need of charging of the borehole which would increase operation costs. An optimal location for a medium-depth borehole would therefore be at a site which has a high cooling demand since in that case the user could benefit from the charging.

Demand-side management with load shifting was chosen as the studied technology from several thermal storage methods which were presented in this thesis. The feasibility of DSM was studied by calculating how much energy the GSHP system could provide during night in order to prevent the heating during four hours in the morning when the electricity prices are high. It was determined that with the use of temperature data from 2017, 92 MWh or 104 MWh of additional energy could be generated during night depending on whether the preheating period was five or seven hours. This would result in saving annually 410 – 460 € if shallow boreholes are used and 350 – 400 € with a medium-depth borehole.

9.1 Limitations

In this study, there were several limitations concerning both GSHP systems and DSM. First of all, the monthly energy consumption of educational buildings was not exact and the monthly consumption of terraced houses had to be estimated by using the consumption of a full year. In addition, as earlier explained, especially the study concerning medium-depth GSHP system included several rough estimations but also the sizing of a conventional GSHP system. These estimations included COP and the amount of energy the ground can provide annually at the study site. The energy production could be more precisely determined for example with TRT which includes drilling at the site and since COP depends both on the ground characteristics and the current conditions at the study site and therefore does not stay constant around the year, COP was only estimated based on previous experience of GSHP systems.

During the feasibility determination of DSM in the educational buildings, besides the uncertainties caused by earlier mentioned factors, the biggest limitation was the lack of information about the thermal capacity of the buildings. The heat losses of the buildings had to be estimated with the use of energy consumption and expected internal heat gains in the buildings. In addition, the evaluation did not take into consideration the heat generated by the sun and the increasing indoor temperature during preheating which results in higher heat loss and increasing energy usage.

9.2 Recommendations

Based on this study, both shallow and medium-depth GSHP systems would be cheaper than the current heating system. The decision between shallow and medium-depth GSHP system depends on whether the economic factors are the most important ones or not. Since shallow boreholes are the cheapest to construct and their construction has clearly less risks than medium-depth boreholes, conventional GSHP system is the wisest decision economically. However, because Iin Micropolis was interested in new technologies, medium-depth GSHP could be recommended because it should provide enough energy for the educational buildings for a reasonable price. Shallow boreholes or other heating methods such as electricity could then be used to heat the terraced houses.

At the moment, there is not an immediate need for renewing the current heating system and therefore it would be recommended to not make decisions about the investment yet in order to gather some more information about the performance of already existing systems since there are already at least one medium-depth GSHP system under construction and one operating in Finland. In addition, if it was chosen to use shallow boreholes to heat the terraced houses, their operation would provide important information about the ground characteristics at the study site. This would allow to make a more accurate estimation of the heat production and feasibility of a medium-depth GSHP system at the study site. The eight boreholes which are required to cover the heating demand of only terraced houses are also much easier to fit to the property than 29 which were needed to cover the heating energy demand of all buildings with shallow boreholes.

Because DSM could only provide approximately 400 € reduction to the annual electricity bill, it is not as economically feasible as the GSHP systems. In 15 years, the savings would only cover 1 % of the investment costs of the medium-depth GSHP system. In this study, only price signals were considered but load shifting could also be done based on incentives, but their use was out of the scope of this thesis. Depending on the investment costs of the system which controls the heating system, it might be more feasible to invest in other kind of DSM technologies such as controlling separately the temperature of each room.

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